PB-240 574

AIR POLLUTION: PROCEEDINGS OF THE THIRD MEETING OF THE EXPERT PANEL ON AIR POLLUTION MODELING, HELD IN PARIS, FRANCE, 2-3 OCTOBER 1972

NATO Committee on the Challenges of
Modern Society

Prepared for:

Environmental Protection Agency

October 1972

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

BIBLIOGRAPHIC DATA SHEET

1. Report No.

2.

PB 240 574

4. Title and Subtitle
Air Pollution, Proceedings of the Third Meeting of the Expert Panel on Air Pollution Modeling, no. 14.

5. Report Date
Oct. 2-3, 1972

6.

7. Author(s)

8. Performing Organization Rept. No. 14

9. Performing Organization Name and Address
NATO Committee on The Challenges of Modern Society, 1110 Bruxelles, Brussels, Belgium

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address
Office of Air and Waste Management, Environmental Protection Agency, Washington, D. C. 20460

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstracts

17. Key Words and Document Analysis. 17a. Descriptors
Air Pollution
air pollution modeling
mathematical modeling

17b. Identifiers/Open-Ended Terms

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

PRICES SUBJECT TO CHANGE

17c. COSATI Field/Group

18. Availability Statement
Available from NTIS

I

19. Security Class (This Report)
UNCLASSIFIED

20. Security Class (This Page
UNCLASSIFIED

21. No. of Pages
308

22. Price PC/MF
9.25/2.25

FORM NTIS-35 (REV. 3-72)

USCOMM-DC 14952-P72

Library
Environmental Protection Agency
Washington, D. C. 20460

PROCEEDINGS of the THIRD MEETING of the EXPERT PANEL on AIR POLLUTION MODELING

A Report of the Air Pollution Pilot
Study, NATO Committee on the
Challenges of Modern Society

*

IV

PARIS, FRANCE
October 2-3, 1972

OTHER NATO/CCMS AIR POLLUTION PUBLICATIONS

Technical Report of the Conference on Low Pollution Power Systems Development, N.4

Proceedings of the Second Meeting of the Expert Panel on Air Pollution Modeling, N.5

Guidelines to Assessment of Air Quality (Revised) SO_x, TSP, CO, HC, NO_x and Oxidants, N.6*

Air Quality Criteria for Sulfur Oxides, N.7*

Air Quality Criteria for Particulate Matter, N.8*

Air Quality Criteria for Carbon Monoxide, N.10*

Air Quality Criteria for Nitrogen Oxides, N.15**

*Also avaliable in French
**Avaliable by Spring 1973, French version by Fall 1973

These documents may be obtained from the NATO Committee on the Challenges of Modern Society, 1110 Bruxelles, Brussels, Belgium, or from the Air Pollution Technical Information Center, Office of Air and Water Programs, Environmental Protection Agency, Research Triangle Park, North Carolina 27711, U.S.A. (English only).

III

PREFACE

Air quality simulation modeling continues to attract widespread attention and plays a critical role in the development of rational approaches for the maintenance of air quality standards. One major aim of the NATO/CCMS air pollution project is to keep the users of models informed as to the current state of the art. Because of the rapid advances in techniques and the diversity of the applications of air quality modeling it has seemed desirable to provide an opportunity for an informal give-and-take exchange of the latest information on modeling and closely related topics. With this objective in mind the participation at the 3rd Meeting of the NATO/CCMS Panel on Modeling, held on 2-3 October 1972 in Paris, France, was widened to include representation well beyond the regular membership countries. All participants were invited to submit in advance extended abstracts in English of the material that they would present. The Environmental Protection Agency, as part of its contribution to the CCMS pilot study, has compiled and published the present proceedings as a permanent record of this material. The Minutes of the 3rd Meeting are also included since they provide some additional information of interest and a summary of the meeting.

R. A. McCormick

R. A. McCormick, Chairman
NATO/CCMS Panel on Urban
Air Pollution Modeling
Director
Meteorology Laboratory
Environmental Protection Agency

PROCEEDINGS OF THE THIRD MEETING OF THE EXPERT PANEL ON AIR POLLUTION MODELING

TABLE OF CONTENTS

CHAPTER		PAGE
I	MINUTES OF THE THIRD MEETING OF THE EXPERT PANEL ON AIR POLLUTION MODELING Kenneth L. Calder, United States of America	I-1
II	OPENING REMARKS R.A. McCormick, United States of America	II-1
III	MODELING EFFORTS FOR COLOGNE F.I. Dreyhaupt, Federal Republic of Germany	III-1
IV	THE NATO/CCMS AIR POLLUTION STUDY OF ST. LOUIS, MISSOURI John R. Zimmerman, United States of America	IV-1
V	PROPOSAL FOR A MATHEMATICAL MODEL OF AIR POLLUTION SURVEY IN MILAN L. Santomauro, Italy	V-1
VI	VALIDATION OF AIR QUALITY SIMULATION MODELS Warren B. Johnson, United States of America	VI-1
VII	THE U.S. REGIONAL AIR POLLUTION STUDY (RAPS) R.A. McCormick, United States of America	VII-1
VIII	AN EVALUATION OF SOME CLIMATOLOGICAL DISPERSION MODELS D. Bruce Turner, John R. Zimmerman and Adrian D. Busse, United States of America	VIII-1
IX	A REVIEW OF SOME TECHNIQUES FOR INVESTIGATING MESOSCALE TRANSPORT IN THE PLANETARY BOUNDARY LAYER Larry L. Wendell, United States of America	IX-1
X	MATHEMATICAL MODELING OF AIR QUALITY THROUGH CALCULATION OF ATMOSPHERIC TRANSPORT AND DIFFUSION Kenneth L. Calder, United States of America	X-1
XI	A SYNOPTIC-CLIMATOLOGICAL STUDY OF AIR POLLUTION POTENTIAL FOR ANKARA Taskin Tuna, Turkey	XI-1
XII	ON THE SELECTION OF SITES OF AIR POLLUTION SAMPLING STATIONS Suha Selamoglu, Turkey	XII-1

✓

CHAPTER		PAGE
XIII	DETERMINATION OF THE ATMOSPHERIC TEMPERATURE AND DENSITY PROFILES FROM FREE DESCENT OR ASCENT OF A SPHERE OF CONSTANT VOLUME AND MASS Suha Selamoglu, Turkey	XIII-1
XIV	AIR POLLUTION EPISODES AND MATHEMATICAL MODELS C.A. Velds, The Netherlands	XIV-1
XV	AN AREA SOURCE MODEL WITH STATISTICAL INPUT, ITS VERIFICATION AND ITS VALIDATION; A STANDARD FOR ODOROUS POLLUTION Louis A. Clarenburg, The Netherlands	XV-1
XVI	STATUS OF THE INVESTIGATIONS OF THE EMISSION INVENTORY OF THE DENSELY POPULATED AREA OF LOWER-MAIN (FRANKFURT) W. Lamp, Federal Republic of Germany	XVI-1
XVII	A SCHEME FOR ESTIMATING THE VERTICAL DISPERSION OF A PLUME FROM A SOURCE NEAR GROUND LEVEL F.B. Smith, United Kingdom	XVII-1
XVIII	THE PREDICTION OF HIGH CONCENTRATIONS OF SULPHUR DIOXIDE IN LONDON AND MANCHESTER AIR F.B. Smith and G.H. Jeffrey, United Kingdom	XVIII-1
XIX	WARREN SPRING LABORATORY Alstair Keddie, United Kingdom	XIX-1
XX	MATHEMATICAL SYSTEM FOR CALCULATION OF SPREAD OF AIR POLLUTION IN THE GREATER STOCKHOLM AREA Björn Bringfelt and Olof Wikström	XX-1
XXI	A COMPARISON OF STABILITY MEASUREMENTS TO PASQUILL-TURNER STABILITY CLASSES Lars E. Olsson, Sture Ring and Sten Ljungkvist, Sweden	XXI-1
XXII	A THREE-DIMENSIONAL TRANSPORT MODEL FOR AIR POLLTUION IN AN URBAN AREA WITH APPLICATION TO SO_2 CONCENTRATION IN OSLO Knut Erik Grønskei, Norway	XXII-1

Chapter I

NATO Committee on the Challenges of Modern Society

AIR POLLUTION

Minutes of the Third Meeting of the Expert Panel on Air Pollution Modeling

Paris, France
2-3 October 1972

NATO/CCMS AIR POLLUTION STUDY
EXPERT PANEL ON MODELING

Minutes of the 3rd Meeting Held in Paris, 2-3 October 1972

Purpose

1. This meeting was intentionally enlarged beyond the regular Panel membership so as to accommodate a broader objective and to encourage a maximum exchange of ideas on a wide front between many of the most active contributors in the field of air quality modeling and closely related topics. Developments and procedures are rapidly unfolding all over Europe and in the U.S.A. that shed light on such important questions as model validation, sensitivity analysis and computation economy. For this reason it was considered desirable to convene an informal give-and-take meeting in anticipation that mutual benefit would be derived by all those participating. All the invitees had been invited to submit in advance extended abstracts in English of the material that they would present. These were distributed prior to the meeting to provide a better basis for discussion. Together with other material that was promised at the meeting, these papers will be available in due course as a permanent and detailed record of the meeting.

2. A list of the participants at this meeting (representing eleven different countries) together with the detailed agenda are appended to these minutes. Also given is a list of the papers submitted prior to the meeting.

Opening Remarks by Chairman (Mr. R. A. McCormick)

3. For the benefit of the enlarged participation at this meeting, Mr. McCormick briefly indicated the origin and history of the NATO Committee on the Challenges of Modern Society, and in particular of the air pollution project (Paper 1). He indicated that the CCMS activities were intended to complement and not duplicate any other international

collaboration. The projects did not involve original research, but were an application of existing knowledge to specific urgent practical problems. At the present meeting some of the most active practitioners in the art of modeling the dispersion of air pollutants in urban areas had been brought together so that they could compare approaches, and it was hoped that the meeting would help to keep users of such models informed as to the current state of development. Although participants were under no formal obligation to provide written contributions, many had already done so and it was intended, in due course, to put these together to represent a "proceedings" in much the same fashion and format as following the 2nd Meeting of the Panel on Modeling.

4. At the opening session Mr. J. Jacquet extended an open invitation for any interested participants to visit the recent wind-tunnel facilities of Electricite' de France at Chatou, near Paris, on the afternoon of Wednesday, 4 October.

Modeling Efforts for Cologne

5. This was an item proposed at the 2nd Meeting of the Panel on Modeling. Dr. F. I. Dreyhaupt (Paper 2) apologized for the fact that he was unable to present an official report on the modeling for Cologne, but the report had yet to be released. The delay was due to a veto by industry involved in the emission inventory studies. In a few weeks time when the report was published, he would arrange to distribute the text and an English translation to members of the Panel, so that a detailed discussion might be possible at the next meeting.

6. Dr. Dreyhaupt indicated that a primary objective was to obtain a listing of all sources of air pollution in a limited region and that more than 300 different components of emission were identified for Cologne. The emissions inventory would also be used as a basis for decision on the optimum locations for air quality sampling stations. The air quality

model that would be used for Cologne was based on the Gaussian plume dispersion formulation of Pasquill and would incorporate Briggs' formula for calculating plume rise. The dispersion conditions were defined by Klug's categories and the diffusion parameters σ_y and σ_z were taken from Klug or Fortak depending upon the roughness of the region. The model assumed infinite mixing depth and could not handle the case of calm or very light winds. The basic model was a short-term one-hour prediction and had not yet been validated. A separate paper containing the main formulae could be made available for the next meeting.

Status of Modeling Studies for Ankara, St. Louis, Frankfurt and Dusseldorf

7. This was also an item proposed at the 2nd Meeting. Dr. S. Selamoglu indicated that there had been no additional modeling efforts for Ankara beyond those already reported at the 2nd Meeting. The long-term climatological dispersion model had not been too successful in predicting the mean concentrations of SO_2 and particulate matter for the winter of 1970 in Ankara, and the model generally overestimated by a considerable factor. The poor agreement could be due to the fact that the theory assumes a flat terrain and a negligible percentage of calm winds. However, the Ankara terrain is of very variable height and the majority of winter winds are light and less than 1.5 m/sec. In discussion, Dr. F. Pasquill suggested that it might be of interest to compare the winter SO_2 concentration levels in Ankara with those occurring in the London smog of 1952 and which had been discussed by Meetham, since the latter situation also corresponded to a stagnant air mass.

8. Mr. K. L. Calder indicated that as part of its contribution to the NATO/CCMS air pollution study the United States had agreed to present a modeling analysis for the City of St. Louis, Missouri, U.S.A. The results had already been summarized in an appendix to NATO/CCMS Air Pollution Technical Report No. 6 and also in a brief paper specially written for the present meeting (Paper 3). Because of its flat terrain and much higher ventilation rate, St. Louis is better suited to analysis

by a simple climatological dispersion model than Ankara, Turkey, and a much improved air quality prediction was indeed obtained. Although the St. Louis region emits more total pollution than Ankara, the measured pollution concentrations are lower for St. Louis. This is probably accounted for in the striking difference in ventilation rates for the two cities, coupled with the fact that elevated point sources deliver most of the pollution over St. Louis in contrast to near-ground sources for Ankara, while at the same time St. Louis extends over an area several times as large as Ankara.

9. A special report on the status of the emissions inventory study for Frankfurt had been prepared for the meeting by Mr. W. Lamp (Paper 14) and circulated in advance. Professor H. Fortak indicated that the inventory was not yet completed and so it had not been possible to apply his model. He referred to the complicated wind structure that occurred with certain wind directions for Frankfurt, when the air flow was over the Taunus mountains, and the necessity for him to develop a special time-dependent model to handle light wind or windless conditions.

10. Professor Fortak also stated that a modeling effort for Dusseldorf was almost completed. This was similar to his Bremen model and permitted calculation of the frequency distribution of SO_2 concentrations at various receptor locations. Validation would be based on comparison with observed air quality statistics for the one-year period 1970-71. For Dusseldorf a large concentration contribution arises from neighboring cities and the Ruhr, and allowance must be made for this in modeling. Transport of pollution to the city from outside is the big difference between Dusseldorf and Bremen.

Modeling for Milan

11. This was an item proposed at the 2nd Meeting, and some current investigations were described by Professor L. Santomauro, of the

Observatory of Brera, Milan (Paper 4). Especially during the winter months Milan is subject to high levels of air pollution, which are aggravated by the peculiar meteorological conditions of stagnation. These include a very low wind speed (~ 0.6 km/hr) and long ventilation time (~ 30 hours) throughout the year, and the persistence of stable conditions in the lower atmospheric layers not only for the urban area, but also the surrounding countryside. Professor Santomauro drew attention to the statistical or regression type of air pollution model that correlates air quality with concomitant meteorological conditions, and to the diffusion type of model the use of which additionally required information on the emissions inventory. For the Milan area, the first step will be the development of a statistical type of prediction model based on available meteorological observations. For the urban area of Milan, there are at present four meteorological stations that have been active since 1958, as well as the central observatory which has been in uninterrupted operation since 1763. This number will be increased in the near future and the information on wind and temperature fed to a central computer. The data will be used to define the characteristics for Milan of the average air flow, of the ventilation time, of the thickness of the atmospheric mixing layer and of the urban heat island. In addition to a statistical regression model, it was later intended to develop a source-oriented meteorological dispersion model.

Criteria for Validation of Air Pollution Prediction Models

12. This topic had also been proposed at the 2nd Meeting of the Panel. The discussion was opened by Dr. W. B. Johnson, Jr. who had prepared a note on this particularly important topic (Paper 5). Dr. Johnson referred to a frequent lack of understanding and communication between model developers and prospective users, leading to models that are difficult or impractical to use and the frequent absence of model performance goals that could serve as standards for validation. Most

efforts at validation had been confined to comparisons of the model calculations with observed air pollution concentrations, although this procedure, which is little more than a calibration, does not provide clearcut information as to the parts of the model responsible for any errors uncovered. It was necessary to recognize clearly that any air quality simulation model contains many submodels, e.g., for emissions, transport and diffusion, transformations and removal processes, and that to establish any high degree of overall confidence it was necessary to evaluate the individual elements.

13. The discussion that followed seemed to indicate a general concensus with this theme, which thanks to Dr. F. Pasquill was conveyed in rough draft to the session chairman as a verse:

> "Calibration may be consoling
> But is a practice we shouldn't condone,
> And for validation to have virtue
> The physics and chemistry must be known."

14. Professor Fortak also briefly referred to the validation procedure that had been employed in his paper presented at the 1969 Chapel Hill Symposium on Multiple Source Urban Diffusion Models. This emphasized the consideration of concentration frequency distributions at strategically chosen locations and their comparison with observation. It was generally agreed that the topic of validation was a particularly important one that merited extended discussion and it was suggested that it be given at least one-half day at the next meeting.

Topics from U.S.A.

15. Four papers had been prepared and distributed in advance of the Panel Meeting. Mr. R. A. McCormick (Paper 6) first outlined the U.S. Regional Air Pollution Study (RAPS), a project to be conducted initially in St. Louis, Missouri, over a five-year period and at a cost on the

order of 25 million dollars. It was the goal of the RAPS project to improve the technical and scientific knowledge of atmospheric processes on scales encompassing major urban centers, i.e., 100-150 km, in order to allow the definition of better air quality management schemes than are presently possible. A major task in this very comprehensive program would be the testing, verification and evaluation of mathematical simulation models to predict the transport, diffusion and transformation of both inert and reactive pollutants over a regional area. This would include evaluation of the accuracy of existing models by comparing predictions with air quality data; identification of specific modules responsible for model inaccuracies and making necessary refinements; development of mesoscale meteorological predictive models to permit use of air quality models in a truly predictive mode; improvement of dispersion formulations particularly for light wind conditions; improvement of chemical transformation formulations; improved formulation for characterizing pollution removal processes in the atmosphere; exercise of developed models and optimization of users' versions to facilitate applications.

16. Mr. K. L. Calder summarized results of a recent EPA evaluation (Paper 7) of six different climatological dispersion models that had been used with point-source and area-source emission data to calculate annual (1969) sulfur dioxide concentrations and total suspended particulate matter for the New York Air Quality Control Region. Two of the models, the Air Quality Display Model and the Climatological Dispersion Model (as previously reported in detail to the Panel on Modeling) used joint frequency distributions of wind speed, wind direction and Pasquill-type atmospheric stability class as meteorological input data. A simplified version of the Climatological Dispersion Model based on use of only a single stability required only a wind direction frequency and harmonic mean wind speed for each direction. The other three simplified models were based essentially on the ideas of Drs. F. Gifford and S. Hanna of

the National Oceanic and Atmospheric Administration. Comparison of these several models was based on calculation of mean annual SO_2 concentrations at 75 locations and total particulate matter at 113 locations, and the comparison of 12 different statistics. The most significant fact established by the study was that it is difficult to improve on the accuracy of the air quality predictions provided by simple models. The predictions of the latter are as highly correlated with measurements as those of more complex models. This suggested that model evaluation studies should routinely include comparison of results with those obtained from simple models applied to the same data.

17. Dr. W. B. Johnson then briefly described some recent techniques for investigating the very complex problem of mesoscale transport in the planetary boundary layer, and that had been developed in the U.S.A. by Dr. Larry L. Wendell et al at the Air Resources Laboratories of N.O.A.A. at Idaho Falls, Idaho (Paper 8). The first topic mentioned was an objective interpolation technique for obtaining wind components at regularly spaced grid points from measurements at non-regularly spaced towers, and illustrations of the uses of the interpolated wind field. Also, the recent use for wind trajectory determination of a radar-tetroon-transponder system mounted on a constant density balloon was described. Some comparisons had been made of trajectories estimated by both the interpolated wind field technique and tetroon observations with observations of the center line location of a plume of methyl iodide gas tracer material released into the atmosphere. These techniques could possibly be helpful in a study of the complex urban wind flow patterns that had already been referred to by several earlier speakers.

18. The final U.S. topic was a short paper that had been distributed in advance of the meeting on mathematical modeling of air quality through calculation of atmospheric transport and diffusion (Paper 9). Mr. K. L.

Calder indicated that it was intended to be used as an appendix in a revised U.S. air quality criteria document for sulfur oxides, that was to be published in the near future. It might be of general interest in providing a bibliography to a large number of recent publications on the topic. It should not be concluded from the numerous references, however, that a corresponding wide variety of modeling approaches was available. In fact, the majority of current mathematical models for both large point-source releases of SO_2 (as for power plants burning fossil fuel) and also the multiple-source situations that characterize urban areas, all stem from the classical Gaussian plume representation of the concentration distribution from a continuous point source. In many cases the differences were primarily matters of detail that were not fundamental, but rather matters of individual preference. Mr. Calder also emphasized the rather convincing recent evidence, based largely on the work of Drs. Gifford and Hanna, that quite major simplification may be possible in multiple-source urban models for stable pollutants, and that the massive numerical effort involved in some recent developments may be drastically reduced without seriously affecting the accuracy of the predictions.

Topics from Germany

19. Professor H. Fortak emphasized the wide interest and feeling of urgent need for air quality simulation models in West Germany and mentioned a recent exhibition stand on air pollution modeling. Even admitting that models were often quite crude, this was better than no models at all, and in West Germany there were numerous requests for air pollution climatology analyses for new factories as models were used as a basis for planning. Professor Fortak also stated that he was attempting to develop an air pollution model for the entire city of Berlin. A difficult first step was an attempt to develop an emissions inventory for the city.

Topics from Turkey

20. Dr. S. Selamoglu discussed three papers that he distributed at the meeting. The first (Paper 11) related to the selection of sites for air pollution sampling stations taking into account various possible uses to which the air quality information might be put, and hence with different distributions corresponding to different considerations relative to the use of the data. This led formally to a problem in the mathematical theory of optimization.

21. A second paper (Paper 12) provided a theoretical analysis relating to the determination of the atmospheric temperature and density profiles from observations of the free descent or ascent of a sphere of constant mass and volume. As Dr. Selamoglu had shown the density profile of the atmosphere could be related to the velocities which would be acquired by a spherical body in its free fall or ascent through the atmosphere. Provided that the velocity history of such a sphere is recorded with sufficient accuracy, this information can be translated to give the density, temperature and pressure profiles of the atmosphere. The practical value of the method, which needs experimentation, was not discussed, although the calculations show promise.

22. Finally, Dr. Selamoglu summarized a paper that had been specially prepared for the Panel by Mr. Taskin Tuna of the Turkish Meteorological Office (Paper 12). This related to a synoptic-climatological study of air pollution potential for Ankara. The study included consideration of such things as variations of the mixing depth throughout the year, the variation in depth of nocturnal surface-based inversions that are frequently associated with high-pressure systems and the frequency of inversions. Also, the SO_2 concentration data that had been obtained earlier for Ankara in connection with the NATO/CCMS air pollution project had been reanalyzed in relation to the synoptic weather features. This study had suggested some empirical rules for forecasting air pollution levels in Ankara in terms of various meteorological factors.

O.E.C.D. Long-Range Transport Model

23. Mr. K. E. Grønskei of the Norwegian Institute for Air Research briefly discussed the modeling effort under the cooperative program of the Organization for Economic Cooperation and Development (O.E.C.D.), to study long-range transport of air pollution in Western Europe. This is primarily related to sulfur compounds in the atmosphere, but will include measurements of acidity in precipitation. The modeling was being done by Mr. Nordo of the Norwegian Institute for Air Research, who was developing an advection type of model similar to that which was being used on a local scale for the air quality simulation in Oslo. Professor Fortak pointed to the difficulty of estimating diffusivity functions in this kind of model from ordinary meteorological observations and Mr. Grønskei mentioned that artificial "numerical" diffusion that was introduced as a result of the finite-difference scheme employed to solve the diffusion equation, was a big problem. Mr. Calder indicated that the latter problem could be largely eliminated by use of a special "particle-in-cell" numerical technique that had recently been developed under an E.P.A. contract. He would be pleased to make available the details of this method. Mr. Grønskei also mentioned an alternative treatment based upon the consideration of Lagrangian trajectories. Dr. C. Velds mentioned a case of trajectory analysis in the Netherlands by means of which a heavy dust deposit that had been observed at the Rijnmond Authority had been tracked all the way back to its origin in Algeria.

Topics from France

24. Messrs. P. Mery and J. Jacquet of Electricité de France, described some recent meteorological and tracer studies being conducted at Fos-Martiques, a location in Southern France, near Marseilles. This presented a very complicated meteorological-dispersion situation due to the presence of a sea breeze. Tracer studies were being conducted with

both SF_6 gas and uranine aerosol injected at the bottom of a chimney stack, in order to compare gaseous and aerosol diffusion. Mr. Jacquet also referred to a special power plant study at Porcheville near Paris. The plant at present has an output of 600 MW, but this will eventually be increased to 2400 MW, and it is necessary to determine the effect of this power increase on the SO_2 pollution from the stack 220 m. high. SO_2 samplers were distributed along a belt extending from Porcheville to Paris and the experiment was based on the burning of special fuel oil of high sulfur content. It had been shown that for the 220 m. stack the maximum effects occurred at downwind distances between 10 - 20 km. This was a very expensive experiment and had cost 6 million francs. Professor Fortak, on the basis of his own experience, expressed the belief that the results should be predictable on the basis of a model.

Topics from the Netherlands

25. Dr. C. A. Velds of the Royal Netherlands Meteorological Institute summarized a paper (Paper 13) that discussed in some detail an air pollution episode that occurred 15 Sept-4 October 1971 in the heavily industrialized area around Rotterdam (called "Rijnmond" as it is situated along the mouth of the river Rhine). During the period an anticyclonic situation occurred with sunny weather, light winds and subsidence. As a measure of the air pollution level the SO_2 concentrations at the 31 sampling sites of the automatic monitoring network in the Rijnmond were used. Meteorological observations included vertical temperature soundings, surface wind speeds, height of mixing layer and estimates of ventilation rate. The study of the relation between meteorological parameters, the SO_2 concentrations and the nuisance experienced by the public during this air pollution episode led to the conclusion that a relation is overruled by small variations (as well in time as in space) in the meteorological parameters and maybe also in the emissions, and that probably it will be impossible to use a mathematical model for these situations.

26. Dr. L. A. Clarenburg of the Rijnmond Authority introduced the concept of the penalization of the environment due to stench, i.e., the percentage of the population living in a given area that was bothered by stench, and indicated that this concept could be described quantitatively in terms of a mathematical model. Such a model had been developed and applied to the situation in five areas in the Rijnmond Authority. Results of calculation were compared with the results of public polls and with the complaint pattern registered by the Central Complaint Office of the Rijnmond Authority. The agreement between calculation and observation was highly significant in a statistical sense. Dr. Clarenburg also referred briefly to an area-source model that he had developed and to an SO_2 model for The Hague, and mentioned an article that had been accepted for publication in the journal "Atmospheric Environment."

Topics from Canada

27. Dr. M. Kwizak of the Atmospheric Environment Service of Canada described the air pollution organization and indicated that modeling was used as a basis for abatement and control. The primary function of his group was research and they were concerned with dispersion modeling, air chemistry research, air quality monitoring and air quality criteria and standards. Canada had strongly supported the WMO global monitoring program. A search was in progress for a city in which to conduct a mesoscale meteorological-pollution study. The group had recently been inundated with requests for information in connection with impact studies and were making analyses for land-use application.

Topics from the United Kingdom

28. Dr. F. Pasquill of the Meteorological Office first described (Paper 15) a new scheme that updated and enlarged one he had developed in 1961 for estimation of the vertical spread of a plume downwind from a near ground-level source. This was intended for use when the preferred direct

measurements of the vertical fluctuations of the wind were not available, and when estimates had to be based on a rather broad description of the meteorological conditions. The first step in this process was to estimate the vertical standard deviation $\sigma_z(x)$ of the cloud, and secondly, to estimate the height of the mixing layer so as to modify the development of $\sigma_z(x)$ at greater downwind distances to reflect the rather slower evolutionary development of the mixing layer.

29. The first step utilized numerical solutions of the two-dimensional diffusion equation out to 100 km downwind, with appropriate vertical profiles of wind and diffusivity suggested by actual measurements in unstable, stable and neutral conditions. The diffusivity profiles were estimated on the basis of the formula given in his 1969 paper presented at the Chapel Hill symposium on multiple source urban diffusion models, namely, $K = \frac{1}{15} \epsilon^{\frac{1}{3}} \lambda_m^{4/3}$ where ϵ is the dissipation and λ_m the equivalent wavelength for peak $n\,S(n)$ in the spectrum of the turbulent vertical velocity fluctuations. This had earlier been proposed as a plausible universal form which could be used irrespective of height and stability in the atmosphere. Estimates of ϵ and λ_m were based on a special program of atmospheric turbulence measurements. Actually, the numerical solutions that were obtained showed that the vertical distribution of concentration was close to Gaussian. The second part of the modified scheme was based on typical observations of the depth of the mixing layer made at Cardington and a developing boundary-layer model recently proposed by Carson at Bracknell.

30. Dr. Pasquill also presented a second paper by F. B. Smith and G. H. Jeffrey (Paper 16) that described a statistical prediction scheme for high concentrations of SO_2 in London and Manchester. This scheme was intended to provide information required by hospitals in these cities and showed a very satisfactory measure of success that was much superior to that obtained using a persistence forecast.

31. Some of the work of the Warren Spring Laboratory was described by Dr. A. Keddie (Paper 17) who indicated a rapidly developing interest in urban air pollution models. Although these would initially be simple ones of the Gaussian plume type, it was also intended to develop advection type models based on numerical solution of the diffusion equation. The latter would involve considerable use of their hybrid computer facility which would also be used in attempts to model the photochemical smog of London. The largest project under detailed consideration was a combined survey-modeling exercise for part of the industrial belt of Central Scotland extending between Glasgow and Edinburgh. This exercise would involve setting up a monitoring network to establish the current distribution of pollution and to validate a model for this area. The model would then be used to assess the effects of increasing the operating capacity of existing plants and to choose the best locations for new emitters.

Topics from Denmark

32. Dr. N. Busch of the Danish Atomic Energy Commission Research Establishment indicated that there was actually little urban pollution modeling activity in Denmark at the present time. An important question related to uses to which models might be put and decisions as to details of prediction that were really necessary. He expressed the view that K-models based on the diffusivity concept might be feasible on the synoptic scale, but not on the urban scale, and also thought that the Gaussian model with rectilinear plume axis might also be of restricted application. Dr. Busch considered that the needs of users of models would be an appropriate topic for another meeting and also the matter of the input data that are needed for application. He also suggested that games should be played with models in simplified situations in order to better understand their properties and potentials, and that model computer programs should be more generally available.

Topics from Sweden

33. Dr. B. Bringfelt of the Swedish Meteorological and Hydrological Institute described the air pollution model that was being developed for the Greater Stockholm area (Paper 18). This was based on the Gaussian plume dispersion concept and was similar in detail to the model that Professor Fortak had earlier developed for Bremen. It was essentially a short-term model from which could be calculated the frequency distribution for the SO_2 concentration occurring at arbitrary receptor locations over an extended period of time. In initial tests of the model it had given quite good agreement with the observed frequency distributions, and both calculated and observed distributions were close to logarithmic normal. Similar projects had been started in Malmö and Gothenburg, and the modeling technique would probably be of great importance to future air conservancy planning in the major Swedish cities. Dr. F. Pasquill commented that in view of the demonstrated success of this type of model for a number of different situations, e.g., Bremen, Reading, Stockholm, etc., it might be that we have already achieved sufficient accuracy with this type of model and we should clarify the question of what more do we expect.

34. Mr. S. Ring of the Swedish Meteorological and Hydrological Service (Paper 19) described attempts being made in Sweden to refine the Pasquill-Turner scheme for estimating the degree of dispersion of airborne materials using routine meteorological observations and the Pasquill-Turner stability classes. Their preliminary results were in agreement with those recently reported in the U.S.A. by Luna and Church (J. of Applied Meteorology, 1972). These suggested that improvement could be obtained by including additional variables and possibly also by using different schemes depending on season and time of day. Stepwise regression analysis was now planned to determine which variables should be used in an optimized Pasquill-Turner class scheme. Dr. F. Pasquill noted that it might be appropriate to caution against continually attempting to refine an inherently crude system by further empirical methods.

Topics from Norway

35. Mr. K. E. Grønskei of the Norwegian Institute [illegible] Air Research described a three-dimensional transport model for air po[illegible]n that was applied to the prediction of SO_2 concentrations in Oslo ([illegible]). Although Gaussian diffusion formulae had been successfully [illegible]n many urban situations, it was considered necessary to develop a K-theory model for the complex wind conditions in Oslo, as the existence of a convergence zone over the center of the city is well-known. The model also recognizes the important influence of the vertical velocity component on the SO_2 concentration field. The conservation equation was solved by finite-difference methods and the problems encountered with artificial numerical diffusion were noted. Several case studies were presented that gave reasonable agreement with observation, even in conditions of weak winds that are often observed in Oslo. It had been estimated that in Oslo vertical transport associated with organized vertical lifting could account for 40-80% of the SO_2 removal from the ground level.

Next Meeting of Panel

36. Mr. R. A. McCormick had earlier indicated his retirement from the Chairmanship of the CCMS Panel on Modeling and that the new Chairman would be Dr. W. B. Johnson, Jr., of the Division of Meteorology of the U. S. Environmental Protection Agency. At a brief meeting following the concluding technical discussion, and attended by the official Panel members from the U.S.A., Germany and Turkey, it was unanimously agreed that the 3rd Meeting had been a very successful one and had met its prime objective of providing wide exchange of technical information relating to air pollution modeling.

37. It was also agreed that:

(a) it was desirable to continue meetings of wide participation at regular intervals. The next should be held in Germany in late May 1973 in order to avoid clashes with other meetings and prior commitments of the Panel members. Germany would shortly suggest a suitable location for this 4th Meeting.

(b) the next meeting should be of three-day duration and centered around six previously chosen and carefully selected special topics. One of these should be a continuation of the discussion on the validation of air quality simulation models. At an early date all members would provide suggestions for the remaining topics, with a final selection resting with the Chairman. The next meeting would be organized along the lines of a workshop.

K. L. Calder

K. L. Calder, Member
NATO/CCMS Panel on Modeling
Chief Scientist, Division of Meteorology
Environmental Protection Agency

MEMBERS AND OBSERVERS OF NATO/CCMS PANEL ON MODELING

3rd Meeting, 2-3 October 1972, Paris

Dr. Bjorn Bringfelt
The Swedish Meteorological and
Hydrological Institute
Fridhemsgatan 9
Postbox 12 108
S-10223 Stockholm 12
SWEDEN

Mr. Sture Ring
The Swedish Meteorological and
Hydrological Institute
Fridhemsgatan 9
Postbox 12 108
S-10223 Stockholm 12
SWEDEN

Mr. Knut E. Grønskei
Norwegian Institute for Air Research
P. B. Box 15
Kjeller, NORWAY

Dr. Niels E. Busch
Physics Department, AEC
Research Establishment Risö
DK 4000 - Roskilde
DENMARK

Dr. Carel Andre Velds
Koninklijk Nederlands Meteorologisch
Institute
De Bilt
THE NETHERLANDS

Dr. Louis A. Clarenburg
Rijnmond Authority
Director, Dept. of Environmental Care
Stationsplein 2, Schiedam
THE NETHERLANDS

Dr. Alistair Keddie
Warren Spring Laboratory
P. O. Box 20, Gunnels Wood Road
Stevenage, Hertfordshire SG12BX
ENGLAND

Mr. C. F. Barrett
Warren Spring Laboratory
P. O. Box 20, Gunnels Wood Road
Stevenage, Hertfordshire SG12BX
ENGLAND

Dr. Frank Pasquill
Meteorological Office
London Road
Bracknell, Berkshire
ENGLAND

Dr. M. Kwizak
Atmospheric Environment Service
4905 Dufferin Street
Downsview 477 (Toronto)
Ontario, CANADA

Dr. Heinz Fortak
Ankogelweg 14
1 Berlin 42
WEST GERMANY

Dr. Erich Weber
Bundesministerium des Innern
53 BONN 7
WEST GERMANY

Mr. W. Lamp
Regionale Planungsgemeinschaft
Utermain
6000 Frankfurt/Main
ZEIL 127, WEST GERMANY

Dr. F. I. Dreyhaupt
Ministerium fur Arbeit, Gesundheit und
Soziales
4 Dusseldorf
Landeshaus, Horionplatz 1
WEST GERMANY

Dr. Werner Klug
Institut fur Meteorologie
Technische Hochschule Darmstadt
61 Darmstadt
WEST GERMANY

Dr. L. Kropp
Technischer Uberwachungs-Verein
Rheinland
D-5000 Koln 30
Postfach
WEST GERMANY

Dr. Suha Selamoglu
Senyuva Evleri
Mertler Sokak 31/6
Ankara, TURKEY

Mr. J. Jacquet
Division Echanges Atmospheriques
Electricitė de France
Boite Postale 24
78 Chatou, FRANCE

Mr. P. Mery
Division Echanges Atmospheriques
Electricitė de France
Boite Postale 24
78 Chatou, FRANCE

Madame Sabine Urban
Université de Strasbourg
22 Rue Schwilgue
67000 Strasbourg, FRANCE

Dr. Gianfranco de Cecco
Divisione di Protezione Sanitaria
E. Controlli
Comitato Nazionale Per L'Energia
Nucleare (C.N.E.N)
Viale Regina Margherita 125
Roma, ITALY

Dr. Ivano Giovannini
Tecneco-Eni
Via Papiria
Fano, ITALY

Dr. Antonio Ditota
Tecneco-Eni
Via Papiria
Fano, ITALY

Professor Luigi Santomauro
Reparto di Geofisica E Meteorologia
Dell 'Osservatorio di Brera
Via Brera 28
Milano, ITALY

Mr. D. H. Slade
Division of Biomedical and
Environmental Research
U. S. Atomic Energy Commission
Washington, D. C. 20545, USA

Mr. Robert A. McCormick (Chairman)
Environmental Protection Agency, NERC
Division of Meteorology
Research Triangle Park, North Carolina
27711, USA

Mr. Kenneth L. Calder
Environmental Protection Agency, NERC
Division of Meteorology
Research Triangle Park, North Carolina
27711, USA

Dr. Warren B. Johnson, Jr.
Environmental Protection Agency, NERC
Division of Meteorology
Research Triangle Park, North Carolina
27711, USA

AGENDA FOR 3rd MEETING OF NATO/CCMS EXPERT PANEL ON AIR POLLUTION MODELING

2-3 October 1972, Paris

Monday 2 Oct.

A.M. - Chairman - R. A. McCormick

0930-1010 - Opening Remarks [R. A. McCormick]

1010-1030 - Item I. Modeling efforts for Cologne [F. Dreyhaupt]

1030-1100 - Coffee Break

1100-1230 - Item II. Status of modeling studies for Ankara, St. Louis, Frankfurt and Dusseldorf [S. Selamoglu, K. L. Calder, H. Fortak]

1230-1400 - Lunch

P.M. - Chairman - K. L. Calder

1400-1430 - Item III. Modeling effort for Milan [L. Santomauro]

1430-1530 - Item IV. Criteria for validation of air pollution prediction models

Item V. Miscellaneous topics relating to air quality modeling

1530-1615 - 1. USA (a) The U. S. Regional Air Pollution Study [R.A. McCormick]

(b) An evaluation of some climatological dispersion models [K. L. Calder]

(c) Some techniques for investigating mesoscale transport in the planetary boundary layer [W. B. Johnson]

(d) On mathematical modeling of air quality [K. L. Calder]

1615-1645 - 2. GERMANY [H. Fortak]

1645-1715 - 3. TURKEY [S. Selamoglu]

(a) A synoptic-climatological study of air pollution potential for Ankara [by T. Tuna]

(b) On the selection of sites of air pollution sampling stations

(c) Determination of the atmospheric temperature and density profiles from free descent or ascent of a sphere of constant volume and mass.

Tuesday 3 Oct.

A.M. - Chairman - S. Selamoglu

Item V (cont.). Miscellaneous topics relating to air quality modeling

0930-1030 - 4. O.E.C.D. long -range transport model [K. Grønskei]

1030-1115 - 5. FRANCE [P. Mery and J. Jacquet]

1115-1145 - Coffee Break

1145-1230 - 6. NETHERLANDS [C. Velds and L. Clarenburg]

1230-1400 - Lunch

P.M. - Chairman H. Fortak

1400-1455 - 7. CANADA [M. Kwizak]

1455-1600 - 8. UNITED KINGDOM (a) Estimating vertical dispersion of a plume [F. Pasquill]

(b) Prediction of high concentrations of SO_2 in London and Manchester [F. Pasquill]

(c) Warren Spring Laboratory [A. Keddie]

1600-1625 - 9. DENMARK [N. Busch]

1625-1725 - 10. SWEDEN (a) Mathematical system for spread of air pollution in the greater Stockholm area [B. Bringfelt]

(b) Comparison of stability measurements to Pasquill-Turner stability classes [S. Ring]

1725-1745 - 11. NORWAY - A three-dimensional transport model for air pollution with application to SO_2 concentration in Oslo [K. Grønskei]

List of Papers Submitted for Panel Meeting

1. Opening Remarks: 3rd Meeting NATO/CCMS Expert Panel on Modeling: By R. A. McCormick, U.S.A.
2. Modeling Efforts for Cologne: By F. I. Dreyhaupt, Germany
3. The NATO/CCMS Air Pollution Study of St. Louis, Missouri: By J. R. Zimmerman, U.S.A.
4. Proposal for a Mathematical Model of Air Pollution Survey in Milan: By L. Santomauro, Italy
5. Validation of Air Quality Simulation Models: By W. B. Johnson, U.S.A.
6. The U.S. Regional Air Pollution Study (RAPS): By R. A. McCormick, U.S.A.
7. An Evaluation of Some Climatological Dispersion Models: By D. B. Turner, J. R. Zimmerman and A. D. Busse, U.S.A.
8. A Review of Some Techniques for Investigating Mesoscale Transport in the Planetary Boundary Layer: By L. L. Wendell, U.S.A.
9. Mathematical Modeling of Air Quality Through Calculation of Atmospheric Transport and Diffusion: By K. L. Calder, U.S.A.
10. A Synoptic-Climatological Study of Air Pollution Potential for Ankara: By T. Tuna, Turkey
11. On the Selection of Sites of Air Pollution Sampling Stations: By S. Selamoglu, Turkey
12. Determination of the Atmospheric Temperature and Density Profiles from Free Descent or Ascent of a Sphere of Constant Volume and Mass: By S. Selamoglu, Turkey
13. Air Pollution Episodes and Mathematical Models: By C. A. Velds, The Netherlands
14. Status of the Investigations on the Emission Inventory of the Densely Populated Area of Lower-Main (Frankfurt): By W. Lamp, Germany
15. A Scheme for Estimating the Vertical Dispersion of a Plume from a Source near Ground-Level: By F. B. Smith, United Kingdom
16. The Prediction of High Concentrations of Sulphur Dioxide in London and Manchester Air: By F. B. Smith and G. H. Jeffrey, United Kingdom

17. Warren Spring Laboratory: By A. Keddie, United Kingdom

18. Mathematical System for Calculations of Spread of Air Pollution in the Greater Stockholm Area: By B. Bringfelt and O. Wikström, Sweden

19. A Comparison of Stability Measurements to Pasquill-Turner Stability Classes: By L. E. Olsson, S. Ring and S. Ljungkvist, Sweden

20. A Three-Demensional Transport Model for Air Pollution in an Urban Area with Application to SO_2 Concentration in Oslo: By K. E. Grønskei, Norway

Chapter II

OPENING REMARKS

3rd Meeting
NATO/CCMS Expert Panel on Air Pollution Modeling
October 2-3, 1972 Paris, France

by
R. A. McCormick

For those of you who are attending a panel meeting for the first time and may not be familiar with the purpose and activities of "Committee on the Challenges of Modern Society" (CCMS), perhaps a few words on the origin and history of this venture would not be out of order.

The CCMS was formally established in November 1969 by the North Atlantic Council of NATO. It represents the mechanism whereby the member countries could extend their practices of the international transfer and application of technology to fields of environmental pollution - also to more general social problems that stem from technological development.

The goal is to show leadership in the solution of existing problems and to develop long-range goals to head off future problems that might be anticipated.

*No one at NATO headquarters is paid by CCMS funds.

*No country participates in projects not of interest to its government.

*No binding rules are made.

*Unanimous support is required to pass resolutions.

*There is no monitoring of compliance, sanctions, or enforcement procedures.

*Projects must not explicitly duplicate other international programs, but complement them.

The method of CCMS operation is through "pilot projects". One country proposes an environmental project that it is prepared to fund - it gets CCMS endorsement and becomes the "pilot" or lead country, with possibly one or more "co-pilot" countries joining in and assuming active roles. The projects do not involve original research, but are to "...boil down existing research with respect to a given problem, lay facts and recommendations before the members, and simulate them to act."

It is my understanding that ten projects have been adopted to date:

1. Open waters pollution (Belgium, France, Portugal)
2. Inland waters pollution (Canada)
3. Road safety (incl. experimental safety vehicle) (U.S., Belgium, Germany, France, Italy)
4. Disaster assistance (U.S., Italy, Turkey)
5. Work satisfaction in a technological era (Britain)

6. Application of scientific knowledge to governmental decision making (Germany)
7. Environmental problems and regional development (France, Britain, U.S.)
8. Advanced health care delivery systems (U.S. and others)
9. Waste water treatment (unknown)
10. Air pollution (U.S., Turkey, Germany, Italy?)

The air pollution project has three primary objectives:

*The assessment of present and future air quality

*The development of air quality criteria

*The assessment of available control technology

The project was divided into two phases. Phase I was concerned with sulfur oxides and particulate pollutants; Phase II deals with hydrocarbons, carbon monoxide, oxidants, and nitrogen oxides, i.e., Phase I primarily industry or stationary-source related and Phase II mobile-source related. The goals are:

Phase I

*An assessment of ambient levels of sulfur oxides and particles, inventory of sources, and projected levels of concentrations.

*Selection of appropriate mathematical diffusion models that relate source emissions to ambient levels.

*Development of criteria documents that relate health and welfare effects to ambient concentration of pollutants.

*Development of control techniques documents presenting the current state-of-the-art for Phase I pollutants.

Phase II

*An assessment of ambient levels of hydrocarbons, nitrogen oxides, carbon monoxide, and oxidants; an inventory of sources of these pollutants and projections of future ambient levels.

*Development of criteria documents for above cited pollutants.

*Development of control techniques documents.

*A low pollution power system program that would provide for cooperation in research and development among member countries in this field.

A brief outline of the progress to date in the air pollution project has been furnished you as well as the "Proceedings of the Second Meeting of the Expert Panel on Air Pollution Modeling."

As we have already indicated in our letters of invitation to you, it was the aim of this, the third meeting of our modeling panel, to broaden the participation in our discussions.

Modeling the dispersion of air pollutants in urban areas is certainly a fashionable occupation these days. And while tremendous advances in the art are hardly to be expected annually, we feel that there would be merit in calling together the most active practitioners to compare notes and take advantage of each other's mistakes. Ot at the very least to commiserate among ourselves over the paucity of relevant source-strength and distribution information, and the non-representativeness of available meteorological data.

Admittedly, in doing this, we also fulfill our obligation to the CCMS in keeping those users of our products informed as to the current state of affairs.

Therefore, I hope that over the next three days that all of you will join in the spirit of this meeting of one of open and contructive informal discussion. Each of you, I know, can contribute something to the enlightenment of us all.

It is our wish to put together for general distribution as many papers or extended abstracts as we can to represent these "proceedings" in much the same fashion and format as for the second meeting of this panel. Mr. Calder will contact you further on this, but you can be assured that a written contribution from each of you is not obligatory - it is entirely up to you.

ACCOMPLISHMENTS

Phase I (SO_x and TSP) Assessment Guidelines have been published (NATO/CCMS #6) as well as results of Assessment Studies for Ankara and St. Louis. Other studies are in various stages of completion at this time. The Guidelines and assessment of Ankara and St. Louis are being revised to include NO_x, CO, HC, and oxidants (Phase II). Working Group Meetings are held every six months prior to the NATO/CCMS plenary meeting to review and report on overall progress of assessment studies and other aspects of the study. The Working Group is composed of one representative from each of the pilot and co-pilot countries.

A model was developed and used in the assessment studies in Ankara and St. Louis by the Expert Panel on Air Pollution Modeling and reported on in the appendices of document #5.

The Expert Panel on Air Quality Criteria has published criteria for SO_x, TSP, and CO. The Panel is currently working on criteria for NO_x.

A meeting is planned for fall 1972 of the Panel on Control Technology to discuss control techniques for SO_x and TSP. Panel members are currently working independently on this subject.

A conference was held in February, 1971 on Low Pollution Power Systems Development. Several nations are considering signing agreements to exchange technical information on this subject. A second conference is under discussion at this time.

GOALS FOR PROJECT*

Revised Guidelines document will be published as will results of all assessment studies now underway.

The Expert Panel on Air Quality Criteria will hold at least one more meeting in Fall 1972 or Spring 1973 and publish criteria documents for NO_x and HC/oxidants.

The Expert Panel on Control Techniques will meet to discuss control techniques for SO_x and particulates during Fall 1972 and will publish control techniques documents for these pollutants. Other pollutants will also be the subject of control techniques documents.

It is expected that several nations will sign multilateral agreements in the near future to exchange information on Low Pollution Power Systems Development (LPPSD). A second conference on LPPSD is being discussed at this time, possibly to be held in Germany in Spring 1973.

---

*Modeling Panel purposely omitted from discussion.

NATO/CCMS PILOT STUDY ON AIR POLLUTION
U.S.A. (pilot), Germany and Turkey (co-pilots)

Task I. Assessment of Air Quality

Guidelines Document
Assessment studies in:
Ankara, Turkey; St. Louis, Mo., U.S.A.;
Frankfurt, Germany; Oslo, Norway;
Milan and Turin, Italy; Rotterdam,
The Netherlands

Task IV. Expert Panel on Control Techniques

Report on control techniques for SO_x, TSP,
CO, HC, NO_x

Task III. Expert Panel on Air Quality Criteria

Report on criteria for TSP, SO_x, NO_x, CO, HC,
oxidants

Task II. Expert Panel on Air Pollution Modeling

Develop models for assessment studies
Report on advances in field

Low Pollution Power Systems Development

Not a panel but conference(s) will be
held to report on advances in field
Signing of multi- and bi-lateral agreements
between nations to exchange information
on subject

Chapter III

MODELING EFFORTS FOR COLOGNE

by

Dr. F. I. Dreyhaupt

Ministerium fur Arbeit, Gesundheit und Soziales
Dusseldorf, Germany

3rd Meeting of Panel on Modeling of NATO Committee on the Challenges of Modern Society

Paris, France, Oct. 2-3, 1972

Modeling Efforts for Cologne

Statement by Dr. F. I. Dreyhaupt

At the last meeting of the Panel, I promised to present an official report of my Ministry concerning the studies on air pollution in Cologne. I must apologize that I cannot do this today as the report is not yet finished. Due to the veto of the industry which was involved in our emission studies, the information could not yet be printed or published. Industry is afraid of identifying the emissions of single firms by the graphs of the report. The report is restricted pending the decision of the Minister.

Please allow me to make the following proposal. When the report is published - maybe in six or eight weeks - we will translate the text and distribute the report and translation to the members of the Panel. Mr. Chairman, I hope that you agree that today I give only a short review concerning the aim and preliminary results of our work in Cologne and that we should have a detailed discussion about the printed report at the next meeting.

What are we doing in Cologne. The first and primary aim is to get a complete emission-inventory, that means a listing of all sources of air pollution in a limited region. For each source or group of sources, we determine the geographic coordinates and the conditions of emission that is to say, the dimensions of the source, quantity and temperature of the exhaust gas, quantity and kind of air pollution components and frequency of emission. The sources are divided into three groups: point-, line-, or area-sources. Systematically, we distinguish three groups of emitters: industry, traffic (especially road-traffic) and residential heating and trade (for instance, gasoline stations, bakeries, slaughteries, etc.). The emissions of the last two groups are calculated by using emission-factors for unit areas of 100m x 100m. The main roads, however, are fixed as line-sources. Emissions of industrial sources are measured, calculated or estimated by experts who do this in collaboration with industrial personnel.

Some interesting results already obtained are:

1. More than 300 different components of emission were found in the industry.
2. In certain industries, for instance, refineries and petrochemical plants, the amount of organic gases and vapors emitted near the ground is relatively high, about 45% below 10m and about 80% below 20m.
3. In the same industries, a large amount of organic gases (about 40%) is diffusely distributed by sources like leakages, tank-losses and so on.

The second aim of our study is to use the emission-inventory for cleaning up the air, that is to say, to improve the basis for political and administrative decisions in the field of environmental protection.

What will we do with the emission-data?

1. We can determine the fractions of the different components in the total emission in a certain area.
2. The data provide a basis for calculating air quality concentrations by diffusion models, for licensing new industrial plants, for town- and regional-planning and last, but not least, for quantitative survey of the different components of air pollution.
3. The emission-inventory is of great importance for the distribution of air quality monitoring stations, that is to say, it may be used to decide on the optimum locations for making measurements.

Our investigations in the Cologne air quality region are not yet completed. The emission-inventory will be completed for this region - about 500 square kilometers in three to six months. Then we will make evaluations as mentioned above. The report mentioned previously contains examples of possibilities for these evaluations. A special example is the calculation of the air quality concentrations in a town region by using a diffusion model. The calculation is simplified, for instance, in regard to the emission-heights and the dimensions of the area-sources. The basis for our calculations is the well-known formula by Pasquill using the Gaussian-distribution. We use the formula by Briggs for calculating the plume rise. The dispersion conditions are defined by Klug's six categories. Diffusion parameters σ_y and σ_z are taken from Klug or Fortak depending upon the roughness of the region. A description of the diffusion model is not included in the report, but we will prepare a separate paper containing the main formulas for the next meeting.

Chapter IV

THE NATO/CCMS AIR POLLUTION STUDY OF ST. LOUIS, MISSOURI

by
John Zimmerman*

ENVIRONMENTAL PROTECTION AGENCY
NATIONAL ENVIRONMENTAL RESEARCH CENTER
DIVISION OF METEOROLOGY
Research Triangle Park, North Carolina

3rd Meeting of Panel on Modeling of NATO Committee
on the Challenges of Modern Society

Paris, France
October 2-4, 1972

---

* On assignment from National Oceanic and Atmospheric Administration
Department of Commerce, U.S.A.

INTRODUCTION

As part of its contribution to the NATO/CCMS Air Pollution Study, the United States agreed to present an air quality analysis for the city of St. Louis. At the same time, a cooperative assessment of air pollution conditions in Ankara, Turkey, was undertaken using parallel methods for both cities. The first appendix to NATO/CCMS Air Pollution Technical Report N.6 contains a complete discussion of the Ankara air pollution program. This NATO/CCMS document presents current methodology used in the assessment of urban air pollution. The second appendix is concerned with St. Louis air pollution.

St. Louis, in the mid United States, is a relatively isolated city, situated on flat terrain. Therefore, the air pollution characteristics of this city have been the recurrent subject of analysis (Pooler 1966, Turner 1969, Peterson 1970), and continue to be of interest as new air pollution information is obtained.

Since sulfur oxide and particulate matter data for St. Louis and Ankara were gathered during the same time and analyzed in a similar manner, they may be compared. Although the St. Louis region emits more total pollution than Ankara, the measured air pollution concentration is lower for St. Louis. Higher air pollution in Ankara stems from the combination of two factors:

a) Greater emissions from ground level pollution sources.

b) Greater frequency of occurrence of extremely light wind speeds.

The air pollution situation between these two cities differs greatly. St. Louis extends over an area several times as large as compact Ankara; the St. Louis terrain is relatively uniform, while that of Ankara is contorted by hills and valleys. Elevated point sources deliver most of the pollutants over St. Louis, while area sources account for less than 20 percent of the sources. In Ankara, the reverse is true.

St. Louis has a much higher ventilation rate than Ankara as indicated by the percentage occurrence of wind-speed range for both cities shown in Table 1. The median wind speed range for Ankara is 0-3 mph; for St. Louis it is 7-10 mph. Hence, were all other elements identical, pollution conditions would be substantially lower for St. Louis than for Ankara.

Because of its flat terrain, St. Louis is more suited to analysis by a simple climatological dispersion model than is the air quality of Ankara. The following analysis uses the same climatological dispersion model (Calder, 1970) applied to Ankara to study the air quality of St. Louis.

Table 1. Percentage of Occurrence of Wind Speed Range for Ankara and St. Louis

	Percent	
Range (mph)	Ankara	St. Louis
0-3	74.8	9.6
4-6	22.9	23.8
7-10	2.2	37.9
11-16	0.1	25.3
17-21	-	2.9
> 21	-	0.5

AIR QUALITY ANALYSIS AND PROJECTION FOR ST. LOUIS

The linear calibration relationship between observed (Winter 1970) and calculated data for St. Louis was found to be:

Sulfur Oxides

Observed Concentration = 0.90 Calculated Concentration + 9 ($\mu g/m^3$)

Particulates

Observed Concentration = 0.47 Calculated Concentration + 49 ($\mu g/m^3$)

These linear relationships were then applied to the model to produce winter, summer, annual (1970), and projected annual (1990) air quality concentrations.

Sulfur Oxides

The computer patterns of seasonal concentration of sulfur oxide, using the 1970 pollution emission inventories, outline the major electrical power, industrial, and residential air pollution sources of St. Louis (Fig. 1-3). The highest concentration of sulfur oxide appears in the industrial East St. Louis area with winter values above 250 $\mu g/m^3$. In Ankara sulfur oxide concentrations are negligible in summer; in St. Louis summer sulfur oxide is still significant even though lower than the winter level. Sulfur oxide concentrations from a major power plant show up clearly to the south of St. Louis. Summer concentrations from this source exceed those of winter. Apparently this is due to the large power demand created by air conditioning units. A power complex to the northeast of St. Louis maintains year-round moderate sulfur oxide concentrations.

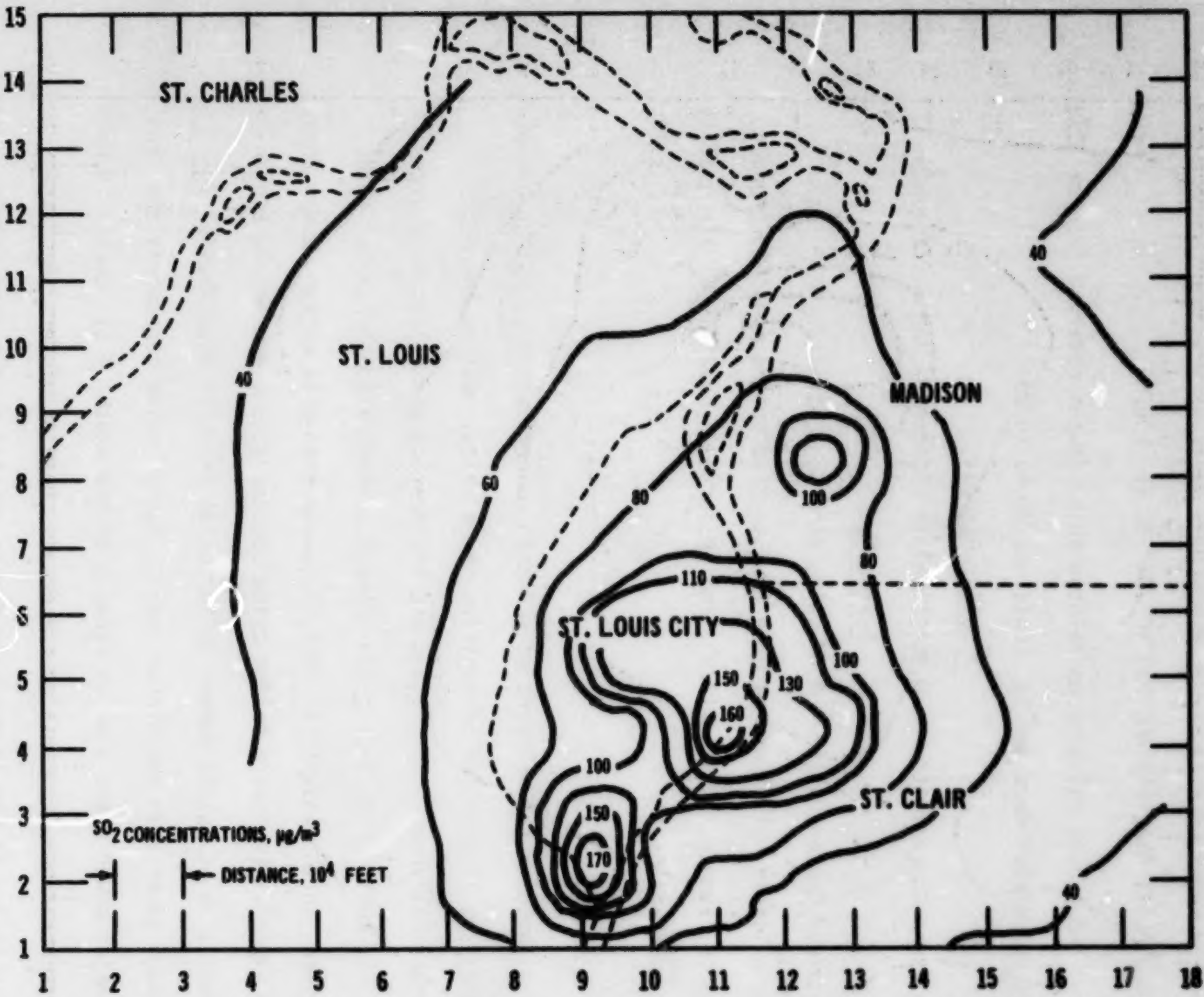

ST. CHARLES
ST. LOUIS
MADISON
ST. LOUIS CITY
ST. CLAIR
40
60
80
100
110
130
150
160
170
SO_2 CONCENTRATIONS, μg/m³
DISTANCE, 10⁴ FEET
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 1. Mean Summer Sulfur Dioxide Levels in St. Louis Predicted by Model (μg/m³).

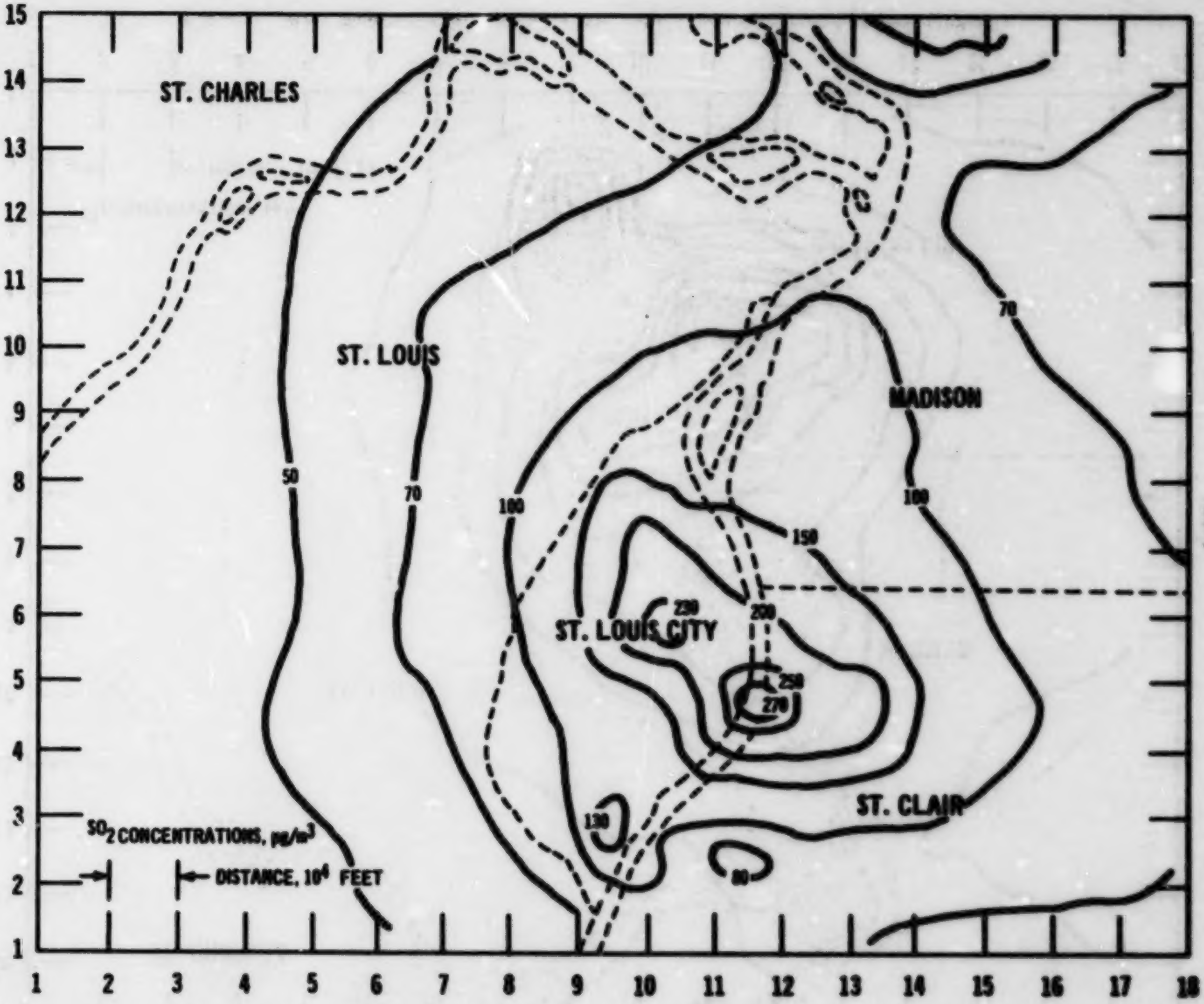

ST. CHARLES
ST. LOUIS
MADISON
ST. LOUIS CITY
ST. CLAIR
50
70
100
150
200
230
250
270
130
80
70
100
SO_2 CONCENTRATIONS, μg/m^3
DISTANCE, 10^4 FEET
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 2. Mean Winter Sulfur Dioxide Levels in St. Louis Predicted by Model (μg/m^3).

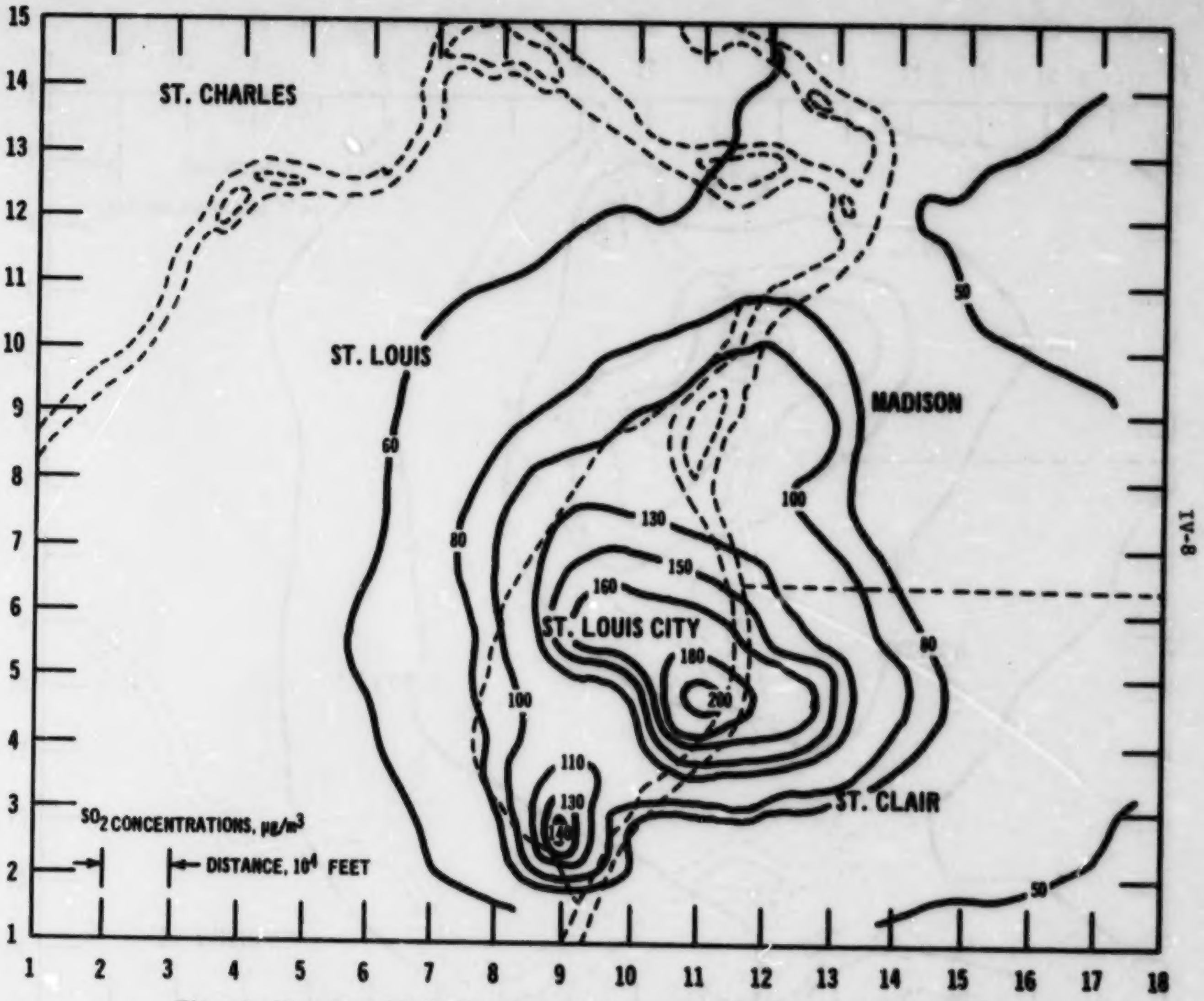

15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
ST. CHARLES
ST. LOUIS
MADISON
ST. LOUIS CITY
ST. CLAIR
50
60
80
100
110
130
140
150
160
180
200
50
SO_2 CONCENTRATIONS, μg/m³
DISTANCE, 10^4 FEET

Figure 3. Mean Annual Sulfur Dioxide Levels in St. Louis Predicted by Model (μg/m³).

The projected sulfur oxide concentrations in St. Louis for 1990 clearly show the effect of pollution controls significantly reducing pollution from the industrial sector of St. Louis (Fig. 4). Increased demands for electric power, however, will result in high sulfur oxide concentrations from electric power generating plants.

Particulate Matter

Analysis of present seasonal data indicates that although higher particulate matter values are found in winter, these do not change as greatly from summer to winter in St. Louis as they do in Ankara (Fig. 5-7). Winter fuel consumption for heating produces maximum particulate matter values of 130 $\mu g/m^3$ in St. Louis. The emission values remain relatively constant throughout the year, so that summer maxima, although lower than in winter, are significant. The projected 1990 pattern of annual St. Louis particulate matter shows the effect of a reduction of about 30 percent in the total annual particulate matter emissions (Fig. 8). This decrease is largely due to the elimination of coal as a heating and commercial fuel, coupled with the use of 99 percent efficient particulate matter control devices. Complete details of the air pollution studies for both Ankara and St. Louis can be found in NATO/CCMS Air Pollution Technical Report N.6, Guidelines to the Assessment of Air Pollution.

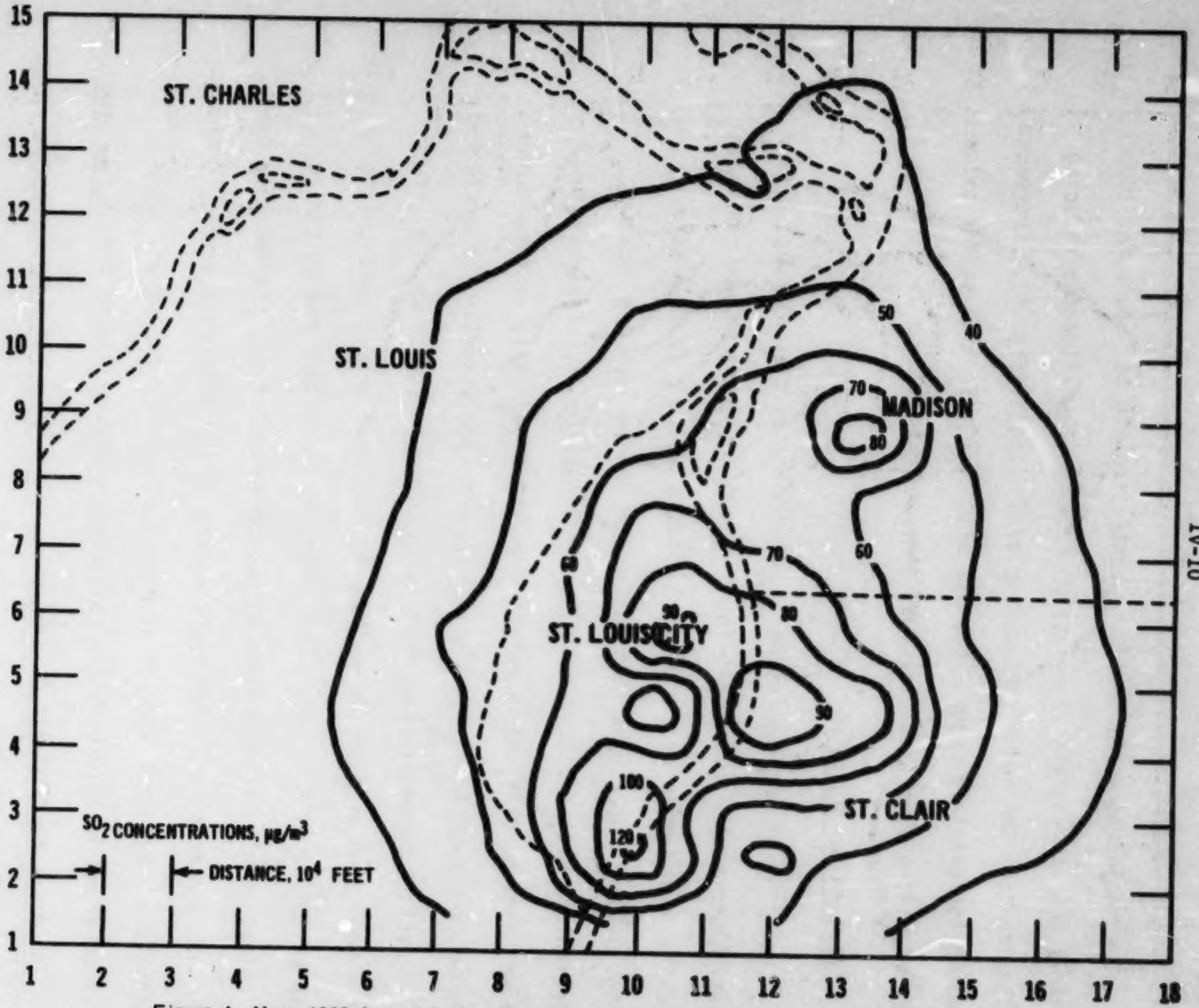

ST. CHARLES
ST. LOUIS
MADISON
ST. LOUIS CITY
ST. CLAIR
40
50
60
70
80
90
100
120
SO_2 CONCENTRATIONS, μg/m³
DISTANCE, 10⁴ FEET
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 4. Mean 1990 Annual Sulfur Dioxide Levels in St. Louis Predicted by Model (μg/m³).

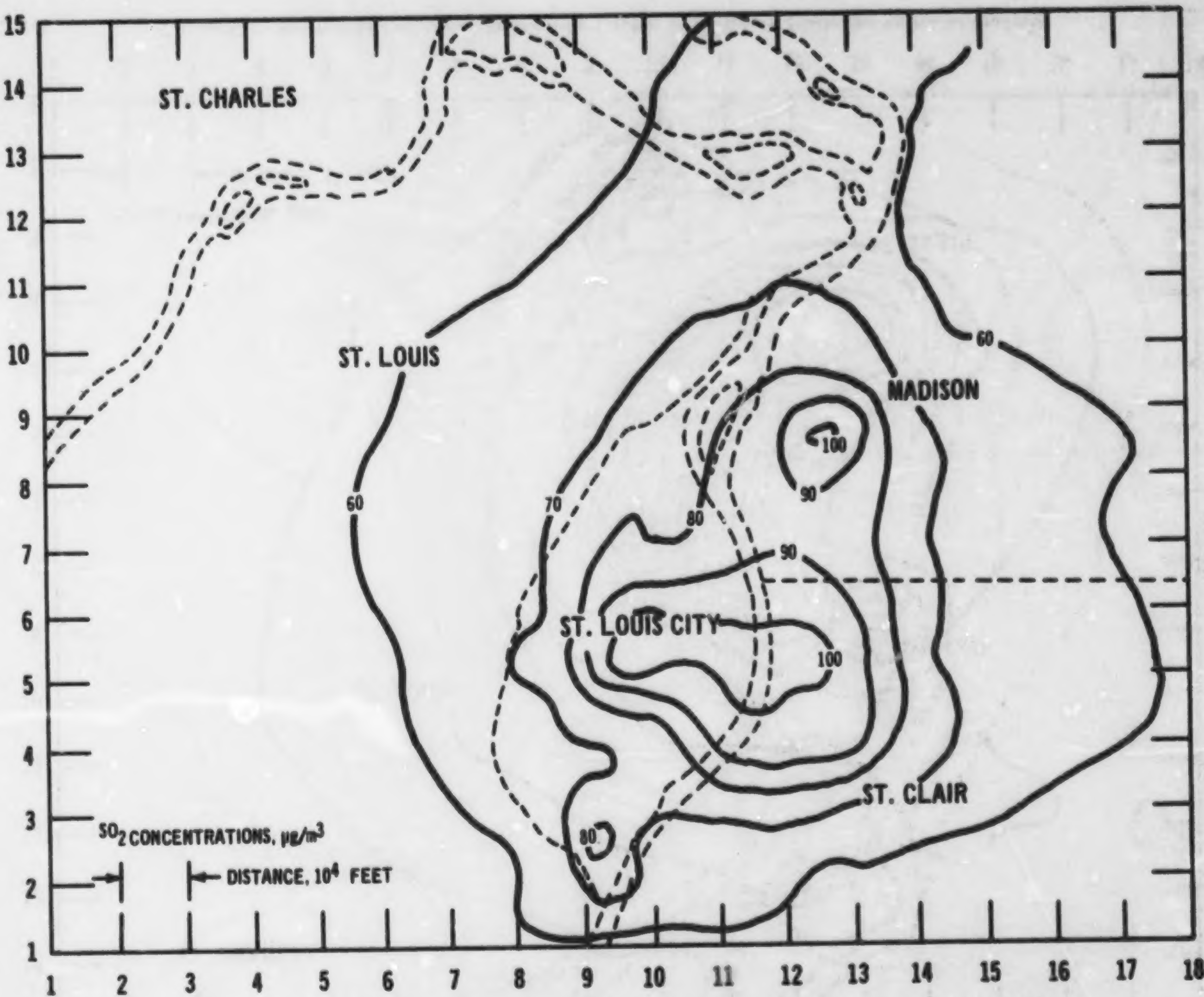

ST. CHARLES
ST. LOUIS
MADISON
ST. LOUIS CITY
ST. CLAIR
60
70
80
90
100
SO_2 CONCENTRATIONS, µg/m^3
DISTANCE, 10^4 FEET
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 5. Mean Summer Suspended Particulate Levels in St. Louis Predicted by Model (µg/m^3).

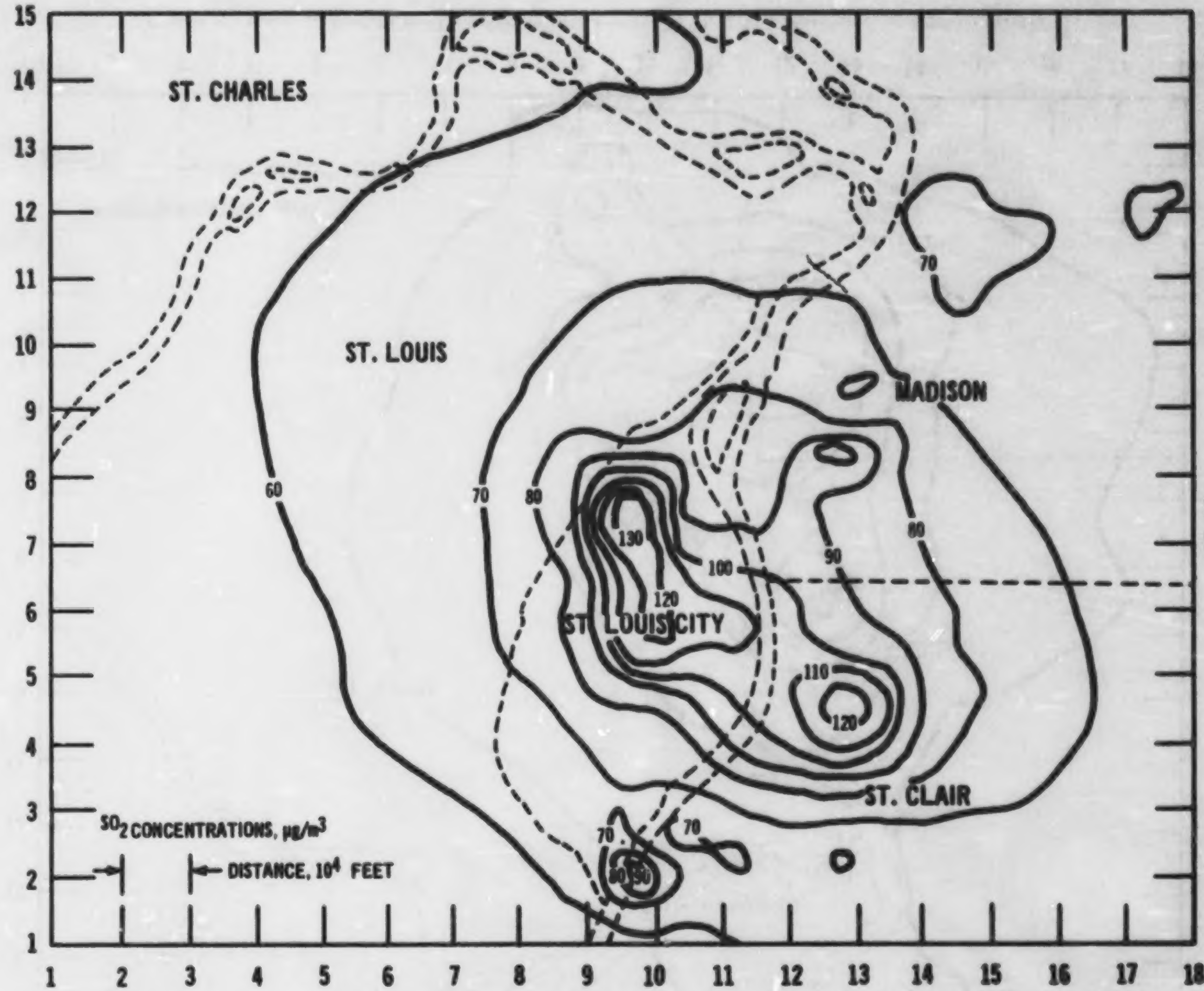

ST. CHARLES
ST. LOUIS
ST. LOUIS CITY
MADISON
ST. CLAIR
60
70
80
90
100
110
120
130
150
SO_2 CONCENTRATIONS, μg/m^3
DISTANCE, 10^4 FEET
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 6. Mean Winter Suspended Particulate Levels in St. Louis Predicted by Model (μg/m^3).

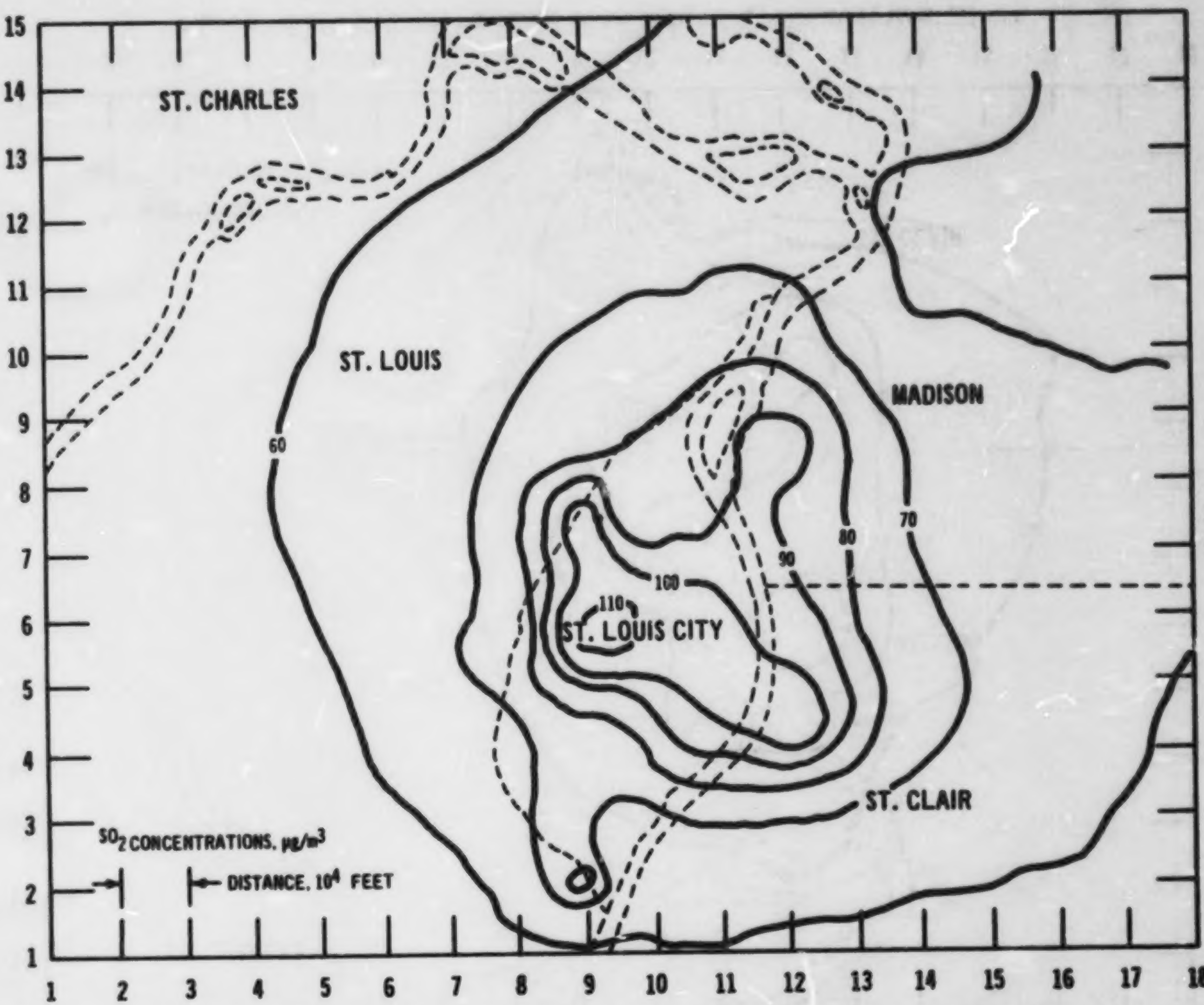

ST. CHARLES
ST. LOUIS
MADISON
ST. LOUIS CITY
ST. CLAIR
60
70
80
90
100
110
SO_2 CONCENTRATIONS, µg/m^3
DISTANCE, 10^4 FEET
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 7. Mean Annual Suspended Particulate Levels in St. Louis Predicted by Model (µg/m^3).

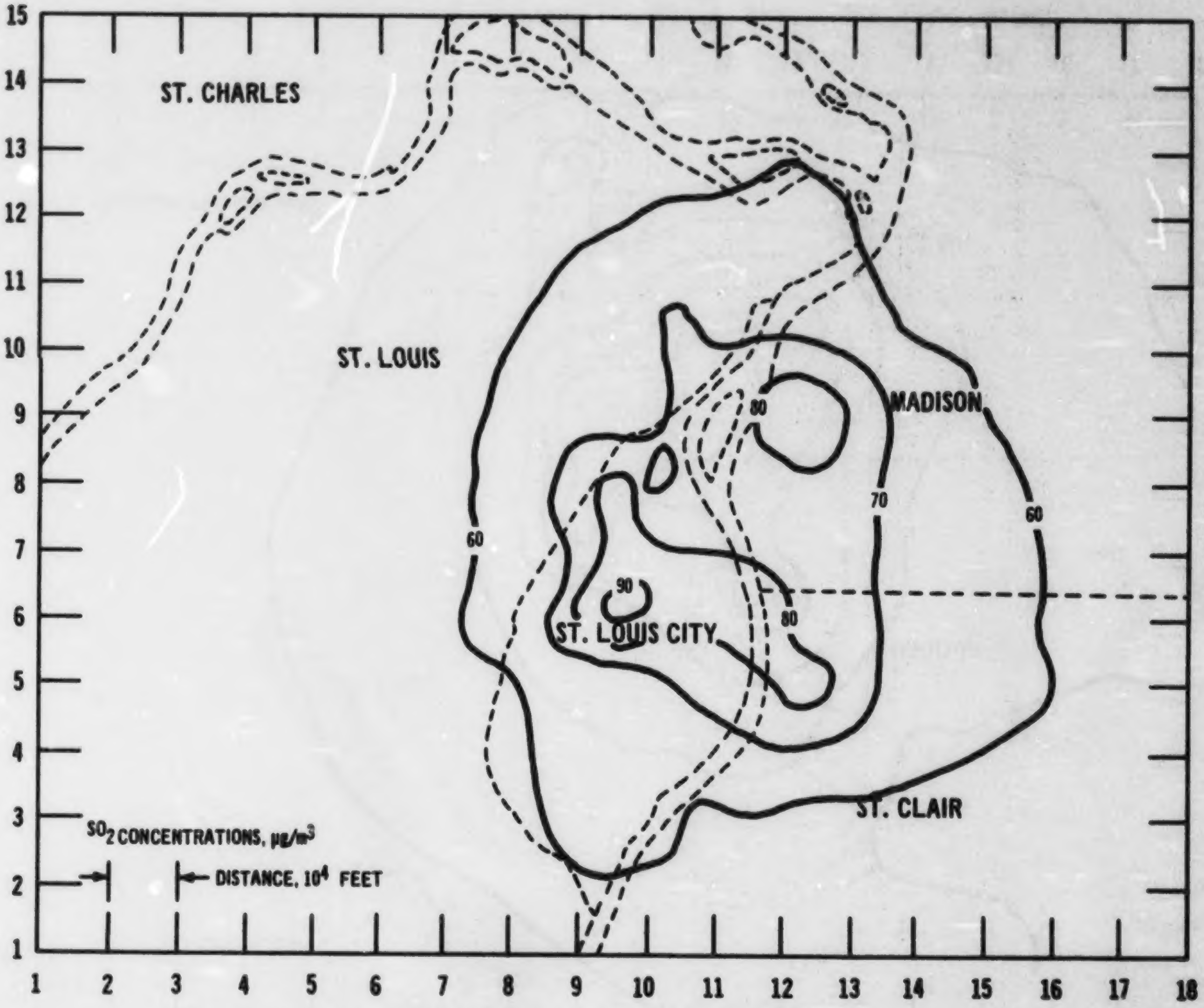

ST. CHARLES
ST. LOUIS
MADISON
ST. LOUIS CITY
ST. CLAIR
60
70
80
90
SO_2 CONCENTRATIONS, μg/m³
DISTANCE, 10⁴ FEET
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 8. Mean Annual 1990 Particulate Levels in St. Louis Predicted by Model (μg/m^3).

REFERENCES

McElroy, J. L., and Pooler, F. Jr., 1968: St. Louis Dispersion Study, Vol. I-II, U.S. Dept. of Health, Education and Welfare, Washington, D. C.

Peterson, J. T., 1970: The Calculation of Sulfur Concentrations over a Metropolitan Area by Using Empirical Orthogonal Functions.

Pooler, F., Jr., 1966: A Tracer Study of Dispersion over a City. J. Air Pollution Control Assoc., 16, 677-681.

Turner, D. B., 1968: The Diurnal and Day-to-Day Variations of Fuel Usage for Space Heating in St. Louis, Missouri. Atmospheric Environment, 1968, Vol. 2, pp. 339-351.

Turner, D. B., 1969: Urban Atmospheric Dispersion Models--Past, Present and Future. Proceedings: Mid-Atlantic States Section, APCA Semi-Annual Technical Conference on What's in the Wind--Meteorological Aspects of Air Pollution Control, Drexel Activities Center, Drexel Institute of Technology, Philadelphia, Pa., March 21, 1969

Calder, K. L., 1970: A climatological model for multiple source urban air pollution. Paper presented at the first meeting of NATO/CCMS Panel on Modeling, 9 October 1970, Frankfurt, Germany.

NATO/CCMS, 1971: Air Pollution Technical Report N.6, Guidelines to Assessment of Air Quality, October 1971.

Chapter V

Third Meeting of Panel on Modeling of the NATO/CCMS

Paris, France

October 2-4, 1972

PROPOSAL FOR A MATHEMATICAL MODEL OF AIR POLLUTION

SURVEY IN MILAN

L. Santomauro

(Istituto di Dinamica dell'Atmosfera dell'Osservatorio
di Brera, Milano)

The urban area of Milan is subject especially during the cold semester to considerably high overall levels of air pollution due, as is the case in all intensely urbanized and industrialized zones, to household, motor vehicles and industrial sources. But in the area of Milan the industrial pollution sources are not entirely located in the outskirts or in the downwind part of the city. Furthermore, the urban area of Milan has other peculiar characteristics in its atmospheric environment which contribute remarkably to increasing and maintaining high levels of pollution; these include scarce ventilation nearly throughout the year and persistence of stable conditions in the lower atmospheric layers not only in the urban area but also at a fairly large radius from the city, especially in eastern and southern sections of the Po valley. The consequence of this on air pollution is very slow mixing of the air layers which at times is almost nil; owing to the peculiar flat orography of the region this phenomenon extends well beyond the urban and suburban sections of Milan.

At this point we may even venture the hypothesis that, in relative terms at least, air pollution is bound to fluctuate constantly around fairly high levels. In fact even if one admits, as one has to admit, that the concentration of contaminants is limited to some extent owing to the strict enforcement by authorities and fulfillment by citizens of the technical regulations, there still remains the problem of the peculiar atmospheric conditions which, as we shall see, do not favor fast transport and prompt dilution of contaminants, whereas all the while the expansion of civil and industrial construction towards rural areas still continues, with the result of further enlarging the area of pollution sources.

Hence, the need for developing a prediction model for air quality which, utilizing the information on emissions along with other useful parameters, may produce air and ground concentration profiles for the various contaminants, of course, only in rough outlines.

From the wealth of literature written on urban pollution forecasting it emerges that these models are either used as a guidance in formulating master plans for the appropriate location of industrial and residential areas or for the assessment of pollution control strategies or otherwise for the operation of alarm systems when pollution levels reach beyond the limits set by the health authorities. It is obvious that, with this modification, these three types of models are apt to fulfill these three types of functions.

In order to be effective, the models must be based on two physico-mathematical processes, i.e., transport and dilution of pollutants, onto a chemico-physical process, i.e., conversion of pollutants in the course of the previous processes and finally two mechanical processes such as gas scrubbing and settling methods of purification.

In merely physico-environmental terms, it may be said that mathematical models can be broken down into climatic-dynamic or statistical models and into meteorological models of diffusion; the former will meet all the routine requirements such as preparation or up-dating of master plans or the developing of a pollution control strategy or, in specific cases, the instant triggering of a pollution alarm system for any particular pollutant.

The second type, i.e., the meteorological model of diffusion would mainly serve to formulate forecasts for specific periods on the overall pollution trends as a function of regional forecasts on atmospheric conditions.

Obviously whereas for the formulation of the statistical model concentration data are required in addition to the climatological parameters, for the meteorological model, on top of the previous data, information concerning emissions will also be needed. Moreover the latter will have to take into account a time factor, whose length must not exceed the term of common meteorological forecasting whether for local or for small-range areas. This prediction term, as meteorologists well know, depends on several variables such as geography and orography among others and in the best instances does not exceed as a rule 24-36 hours. This prediction term may be prolonged only if the meteorological information for the urban area is supplied not only by airport stations of the area or by the normal synoptic network, but also by a regional network subject, of course, to geographic and orographic factors.

Our approach to the development of a prediction model for the area of Milan includes as a first step the preparation of the climatic/dynamic model as based on existing meteorological observations.

In fact in the urban area of Milan there have been four meteorological stations active since 1958 as well as a central observatory which has been uninterruptedly in operation ever since 1763; on the whole at present there are five data gathering sites, whose number will be raised to 12 before the end of the year. The urban area of Milan unfolds around one single center and the Brera observatory is practically at the center of the conurbation; the four stations are sited in the interior part, so that the other seven will be located at the farthest reaches of the peripheral area of Milan. Still in the course of this year the 12 stations will be connected to a computer that is to receive real time wind and temperature data. Another station available is fitted onto a 110 m high metal tower in the Park of the Sforza Castle and performs continuous measurement of the lapse-rate, wind intensity and direction at two distinct levels of which one is at 115 m of altitude. Also this station is to be connected with the computer. Finally we may take into consideration the Radiosonde station of the Air Forces in the Linate airport which is at approximately 6 km as the crow flies from the city center.

With all these facilities at disposal, after establishing the climatic/dynamic model, it will be possible to pass on to working out the meteorological model of diffusion, after appropriate examination of the emission parameters. The operational steps in establishing the climatic/dynamic model for the urban area of Milan are as follows:

(1) determination of the average direction of air mass motion and of small scale vorticity

(2) determination of the frequency of "ventilation time" as based on the prevailing air mass flow path

(3) determination of the thickness of the atmospheric mixing layer

(4) determination of the "urban heat island".

The first and second steps, i.e., determination of the average direction of the air masses reaching the urban area of Milan and of small scale vorticity as well as information on the frequency of ventilation, will serve to identify the main phenomena affecting the emission and transport of contaminants. Considering the orographic and topographic situation, which is fairly simple in the case of Milan, it seems that one anemometric station may be sufficient to determine the motion of the air masses over the whole urban region, after the method followed in many other models. However, one must bear in mind that, as measured at ground level (and here ground level is meant in the sense of the standard set forth by the World Meteorological Organization) or slightly above ground, the winds are hardly at all representative of altitudinal wind flows even as low as one hundred meters above ground.

In fact the correlation of the data gathered by the five observation sites showed that the incoming air masses enter the urban area of Milan mostly from SSE and that at least the winds in the velocity range up to 18 km/h do not follow a very uniform direction of motion but rotate as a rigid cyclonic system around the central area of the city at a very slow radial velocity (Santomauro L. - 1971). In the literature the ventilation time is said to vary usually over a range of 2 to 12 hours in big cities with light winds. Still in Milan, where the wind has a mean velocity of 0.65 km/h when the air mass moves in the direction of the resulting wind (coming from 161°) the ventilation time appears to be more than 31 hours. This suggests that the air mass entering from a peripheral SSE point becomes remarkably polluted when it reaches the NNW part. The third and fourth steps, i.e., determination of mixing layer thickness and identification of the "urban heat island" concern that part of the climatic/dynamic model which is basic for the understanding of the phenomenon of dilution of gaseous pollutants. The thickness of the mixing layer is of great importance in the field of urban air pollution problems because this is the layer, as measured vertically from the ground, where the pollutants are supposed to mix due to the agency of convective flows originating from daytime heating at ground level; it is associated with the heat island which usually forms in urban areas around the center, wherein the mean temperature is higher than in the periphery. Quite clearly the presence of a mixing layer implies the existence of a temperature inversion with the upper boundary of the mixing layer corresponding to the bottom of the inversion layer. Therefore, the mixing and dilution of the pollutants entering the atmosphere are dependent on the degree of air turbulence. In most types of atmospheric conditions, the velocity of dilution due to turbulent mixing is at least 1000 times greater than the dilution velocity resulting from the molecular diffusion of gases. The velocity of turbulent mixing is highly variable and may be computed only from thermodynamic diagrams. It is the main factor in the determination of pollutant concentrations over several kilometers from the emission sources.

From the literature it emerges that the accuracy of the prediction models largely depends on the precision they afford in computing dispersion velocity whose rate may vary a great deal over distances of several kilometers in the horizontal direction, especially when changes occur in the thermal and physical characteristics of the surface beneath. These changes are much faster in the vertical direction; as a matter of fact, the mixing rate may even differ by a factor of 100 between the mixing layer and the inversion layer of the atmosphere.

It is a known fact that in order to calculate the mixing layer of the air, one must use the data of vertical temperature sounding, usually supplied by the main airports and in the case of Milan by the Meteorological Service of the Air Forces at Linate. Since in the urban area of Milan there are at the moment five meteorological stations which among others provide the means for calculating potential temperature, a simple computer program may suffice to calculate the thickness of the mixing layer at five points of the city and then relate it to that of Linate outside the suburban area of Milan.

For the determination of the mixing layer the system in use now is the one adopted by the Environmental Science Services Administration, that is to say the time division is on a monthly basis, the mixing layer classes are divided into eight intervals, i.e., intervals of 250 m up to 1000 m altitude, intervals of 500 m up to 3000 m; moreover the thicknesses of the mixing layer are related to various wind velocity class intervals; finally one must also take into account the hours of persistence of every specific layer and the atmospheric conditions over the 12 hour period.

This work will be accomplished during the current year and is already in an advanced stage of progress. It will be accompanied by a survey on the variations at the surface boundary layer of the earth's atmosphere; this survey is already available for the locality of Linate and it will be completed for the urban area of Milan as well (Santomauro L. - 1968). As to the meteorological model of diffusion for the urban and suburban areas, a statistical breakdown of emissions is needed, as mentioned already at the beginning of this report.

In fact specialists know that in most urban air pollution models a uniform horizontal grid is used as divided usually into squares of 500 m up to 10 km in lateral size. The dimensions adopted vary depending on the application for which the model is intended and on the precision of the data supplied to the model. It is worth mentioning that in some instances use is made of the so-called "telescopic grid" wherein the grid squares of the urban center--assumed to have a more variable pollutant emission level--are smaller in size then those of the peripheral and rural areas.

It is our intention to apply to the Milan area a grid of approximately 56 square elements each sized 2 km per side. We prefer the regular grid over the telescopic one because there seem to be no major differences between the emission levels inside the circle of the Naviglio canals (Cerchia dei Navigli) as compared to the areas outside the circle. It must be borne in mind that in addition to the automobile source, there are other smaller or greater pollution sources distributed over the Milan area; these could be classified after the method suggested by Fortak for the Bremen model, so as to cover all the sources contributing not less than 0.02% to the urban emissions. As a result, the major simple sources would be indicated individually as such in the actual point where they are located whereas the small sources would be cumulatively shown within the grid square. Although this method is of little use in computing concentrations in the neighborhood of the sources still it has the benefit of offering a high degree of precision over distances covering several grid squares.

Another aspect to be considered is the actual height of the major emissions whether stemming from industrial sources or heating plants. It is a well known fact that there is a wealth of mathematical models available for calculating the height of the plume and it would be useless to list them all in this paper. Just now it is the three varieties of the Briggs model that are preferred (as adopted by the American Environmental Protection Agency - EPA, by the U. S. Atomic Energy Commission - USAEC, and by the Verein Deutscher Ingenieure - VDI) because it displays remarkable advantages over the other models and has the remarkable benefit of providing a closer approximation to actual facts.

We know that in the other models ever adopted to date the wind parameter had to be a real dimension so that the models could not be utilized for low wind velocities or wind calms; the reason for this was that in the others plume-rise models being the anemometric parameter at the denominator of a fractional expression, the height of the plume in case of windspeeds nearing zero would tend to infinity, which is absurd. However, this variety of the Briggs' model is applied very well to the air of Milan where, as we unfortunately all know, there are very long periods of air stagnation. Another advantage of the Briggs' method is given by the fact that under unstable conditions it also takes into account the stack heights, which from an aerodynamic point of view is of considerable importance because it is one thing if an effluent is emitted at 10 m above ground and quite another if the emission is at 100 m; all this has significance especially in the case of stacks rising in the urban area where the soil is occupied by obstacles of different shapes and volumes.

As regards the actual height of the smaller sources, since these have natural draught, it is possible to use the model of Fortak which presupposes an actual height of 25 m, at least I think this is the correct figure, for emissions of sulfur dioxide in the lower part of Brera and of 15 m in the peripheral areas of the city.

It is to be noted that uncertainties as to the actual height of the sources and plume axes may induce into very severe mistakes in model computation especially for comparatively short distances. Over greater distances, however, the importance of stack heights is less because the plumes from very high stacks often fail to fit the gaussian model of the plume itself--onto which the ground concentration model are based. In fact these plumes often remain in the air only for a short time, at the bottom of the inversion layer or within the layer itself, and they expand towards the ground as soon as the stability of the lower part of the atmosphere undergoes a change.

Emissions from automobile traffic in the roads are often represented in the models as linear sources and roads may be represented as succeeding straight segments. If we assume the emission rate as constant along every segment it is then possible to calculate directly the concentration areas produced by every linear source, considering the constituents in the direction of the wind and perpendicular to it for every possible wind direction. I have hinted to this type of emissions only in order to make this report as comprehensive as possible but tomorrow we shall hear more details on this section of pollution from experts.

At the beginning of this synthetic presentation I said that one of the main characteristics of Milan is the persistence of atmospheric conditions that favors in turn the persistence of high levels of pollution. But which is the actual volume of gas emissions from the various sources into the atmosphere of the Lombard metropolis?

Let us refer to the research carried out by Capponi in 1968 (Capponi, A., Palmizi F. - 1968); according to this author in 150 days of household heating the average volume of gas emissions would be 5,100,000 Nm^3/h to provide 20°C heating, with a peak (in the morning) at the time when fires are lit - equal to 9,850,000 Nm^3/h. The daily average given for the industry is of 2,600,000 Nm^3/h with a peak of 3,000,000; motor vehicles traffic yields as an average 2,000,000 Nm^3/h with a peak of 3,600,000 during the rush hours (these figures were calculated on the basis of 50,000 vehicles averaging 20 HP, all circulating at the same time during the rush hours in the cold days).

On the whole during the period of heating the emissions into the atmosphere of Milan are as an average of 9,700,000 Nm^3/h, this quantity being mostly trapped into the air for several days and accumulated owing to the atmospheric conditions mentioned.

In regard to the pollutants Capponi states that sulfur released into the air in the form of sulfur dioxide over 150 days averages 230 Q/h and in the cold days (i.e., with external temperature equal to -5°C) the figure reaches as high as 350 Q/h with a dust level of 2300 and 3500 kg/h; these assessments were made on the basis of 0.3 g/m^3 gases.

Moreover the pollution levels for sulfur dioxide alone exceed 1.5 ppm in some points of the city, especially in the center; these levels are more frequent in the months of December and January when the thickness of the mixing layer is reduced to the minimum and the regrettable phenomenon of "fumigation" is most conspicuous thus enhancing pollution relentlessly.

The atmospheric conditions of the regional area are what they are and there is certainly no way for interfering with them; so we have to work on the emission sources. Thus the climatological and meteorological part of the models will have to be integrated and correlated with the part dealing with emissions and concentrations. This matter will have to be handled with the urgency it calls for, thus we must undertake at once the preparation of the models. However, it must be pointed out that the mathematical models--whether designed for the determination of the actual stack heights or for the computation of ground concentrations or even for diffusion over the urban area--are not to be regarded as absolute, nor used as a sort of ready reckoners or a means for scientific speculation; in order for them to be effective and real they must be interpreted in the light of the assumptions on which they are based and continuously adjusted to the physical environment. Only in this case will they result in a valuable aid to the authorities responsible for public health and hygiene.

Bibliography

1. Caponi, A., F. Palmizi, 1968, Contributo degli impianti di riscaldamento civile all'inquinamento atmosferico. Atti VIII Convegno Nazionale del Riscaldamento e della Ventilazione, Padova.

2. Santomauro, L., 1968, Determinazione dell'andamento medio dello spessore dello strato limite superficiale dell'atmosfera a Milano (Linate) con il metodo di Laikhtam - Annali di Geofisica - Vol. XVII - Supplementi Meteorologici N. 18 dell'Osservatorio Astronomico di Milano - Merate.

3. Santomauro, L., 1971, Analysis of Wind Trends in an Urban Area Situated on Flat Land - Supplementi Meteorologici N. 21 dell'Osservatorio Astronomico di Milano - Merate.

Chapter VI

VALIDATION OF AIR QUALITY SIMULATION MODELS

by

Warren B. Johnson*

Division of Meteorology
U.S. Environmental Protection Agency
Research Triangle Park, N. C.

---

*On assignment from the National Oceanic and Atmospheric Administration

Third Meeting, NATO/CCMS Panel
on Urban Air Pollution Modeling,
Paris, 2-4 October 1972

VALIDATION OF AIR QUALITY SIMULATION MODELS

Warren B. Johnson
Division of Meteorology*
U.S. Environmental Protection Agency
Research Triangle Park, N. C.

I. INTRODUCTION

Over the past few years, many models have been developed that calculate the distribution of air pollutant concentrations in space and time [here such models will be referred to as Air Quality Simulation (AQS) Models]. However, very few of these models have ever been applied to any large degree to practical air pollution control or planning problems. One reason for this is simply a lack of understanding and communication between AQS model developers and prospective users, leading to models that are difficult or impractical to use.

A contributing element here has been the frequent absence of model performance goals that serve as standards for validation. Setting such goals is not a straightforward matter, since they must necessarily reflect the intended use of the model, as well as the capabilities of the users, and must also involve a number of compromises between such things as accuracy, resolution, and computation time. In view of the current state-of-the-art of modeling, the best policy here is likely to be as liberal in the specifications as the intended model application will permit, rather than strive for some desirable, but unnecessary and possibly unattainable goal.

---

*)On assignment from the National Oceanic and Atmospheric Administration

However, perhaps the most important factor that has discouraged extensive model application has been a general lack of confidence in their capabilities. This follows from the fact that few models have been adequately evaluated and validated*, because of the general lack of suitable data. To gather more data requires field programs, which are expensive. However, the importance of this problem has now been generally recognized, and plans to alleviate the situation are underway, as will be mentioned later.

In the absence of resources for special data-gathering programs, modelers have had to rely upon available data for checking their models. Most efforts have been confined to comparisons of the model calculations with observed air pollutant concentrations. This procedure, which is little more than a calibration, can yield clues about which parts of the model may be responsible for any errors uncovered. However, the adjustments that are made do not usually contribute to confidence in the generality of the model, unless the latter can be proven through the use of data from several cities. Indeed, it is quite possible for a model to have defective, but compensating, elements, which overall may give adequate agreement with air quality observations for the "calibration" city, but nowhere else.

In contrast, a true evaluation and validation program must involve the evaluation of individual model elements, on the basis that the whole can be no better than the weakest component part.

---

*)In this discussion the terms "evaluate" and "validate" are used interchangably, and taken to have almost the same meaning. Strictly speaking, however, a model must be evaluated (dictionary: "appraised carefully") as a necessary step before it can be validated (dictionary: "confirmed").

II. STRUCTURE OF AN AQS MODEL

It is appropriate now to consider the arrangement of elements making up an AQS model, as indicated in Fig. 1. This figure also illustrates in concept the complete process involved in applying a hierarchy of related models to help reach a decision on a prospective air pollution control strategy or land-use plan. Of course, many of the individual models illustrated as part of the overall system are not yet available, such as Elements 5, 6, and 8, but even without them, the loop can be closed and useful guidance obtained from the system.

As indicated, there are three main elements of an AQS model:

(1) Submodels for conversion and estimation of required model inputs;

(2) Main modules or physical formulations (emissions, transport and diffusion, transformations, and removal); and

(3) Calibration procedures (if required).

It is not always recognized by those not thoroughly familiar with the subject that the submodels for estimating inputs are a major part of AQS models. This arises because of the fact that almost none of the input variables for the main modules are directly observed or routinely available in sufficient detail. The submodels, then, must convert, estimate, and interpolate from available data to provide the detailed fields of input variables that AQS models require. In fact, some of the submodels require meteorological modeling of processes that have not yet been well described or measured.

III. REQUIREMENTS FOR EVALUATION OF MODEL ELEMENTS

In this section some of the problems that should be addressed in a model evaluation program will be discussed, and examples of possible approaches will be presented.

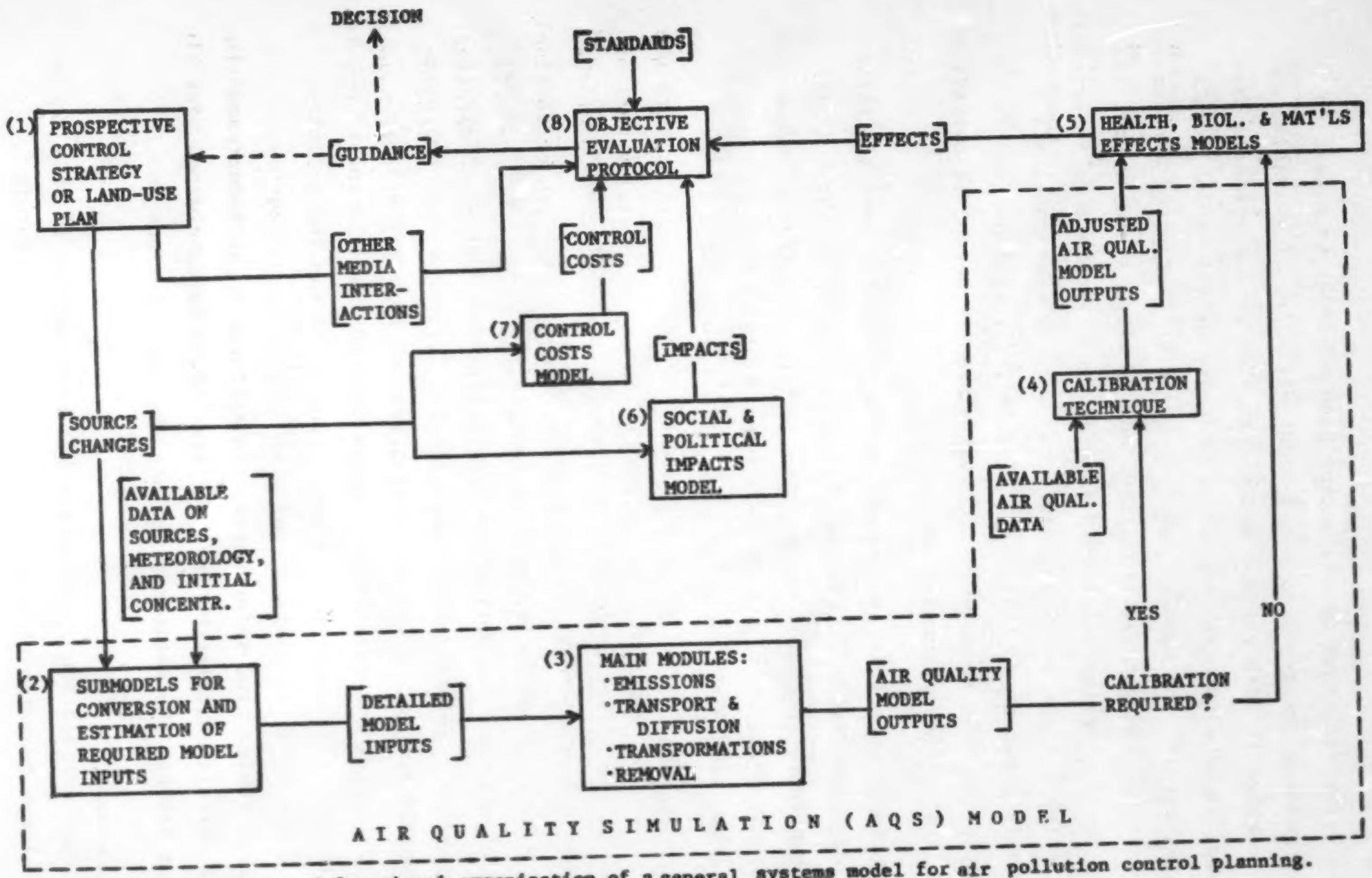

DECISION
STANDARDS
(1) PROSPECTIVE CONTROL STRATEGY OR LAND-USE PLAN
GUIDANCE
(8) OBJECTIVE EVALUATION PROTOCOL
EFFECTS
(5) HEALTH, BIOL. & MAT'LS EFFECTS MODELS
OTHER MEDIA INTER-ACTIONS
CONTROL COSTS
(7) CONTROL COSTS MODEL
IMPACTS
(6) SOCIAL & POLITICAL IMPACTS MODEL
SOURCE CHANGES
AVAILABLE DATA ON SOURCES, METEOROLOGY, AND INITIAL CONCENTR.
ADJUSTED AIR QUAL. MODEL OUTPUTS
(4) CALIBRATION TECHNIQUE
AVAILABLE AIR QUAL. DATA
YES
NO
(2) SUBMODELS FOR CONVERSION AND ESTIMATION OF REQUIRED MODEL INPUTS
DETAILED MODEL INPUTS
(3) MAIN MODULES:
·EMISSIONS
·TRANSPORT & DIFFUSION
·TRANSFORMATIONS
·REMOVAL
AIR QUALITY MODEL OUTPUTS
CALIBRATION REQUIRED?
AIR QUALITY SIMULATION (AQS) MODEL

Fig. 1. Elements and functional organization of a general systems model for air pollution control planning.

Submodels

The basic technique in evaluating each submodel is simply to directly measure the required model input variable, if possible, and then to compare it with the estimates furnished by the submodel from available, gross data. For example, a meteorological (main) module typically requires the spatial and temporal distribution of wind speed, wind direction, atmospheric stability, and vertical mixing depth, all of which the meteorological inputs submodel must estimate or interpolate from existing surface and upper-air data, such as that routinely available from the nearest airport. Special, direct measurements of these variables on a relatively detailed scale are needed to establish the validity of the individual submodels.

Especially uncertain are current capabilities for modeling three-dimensional flow fields in complex settings, such as in the vicinity of topographical, urban, or marine influences. Accordingly, evaluation of these submodels, through such techniques as trajectory tracing with constant-level balloons, should be emphasized.

Emissions Module

This is apt to be the weakest portion of the entire AQS model, and clearly has a direct effect on the overall model accuracy. Currently there is almost no way to evaluate an emissions module, except through sampling of effluent concentrations from individual sources, which is quite expensive. An alternative experimental technique that may have merit involves the use of remote-sensing devices to measure line-integral pollutant concentrations*. When used in a single-ended, mobile, vertically pointing mode, such an instrument could map the pollutant loading in the vertical plane around a source, group of sources, or an entire city. Using wind information, the pollutant mass budget and thus the gross emission within the enclosed area could be determined, for comparison against the estimates produced by the emissions module.

---

*)A Barringer correlation spectrometer has been applied in this way by Environmental Measurements, Inc., San Francisco, California.

Also still unanswered are questions about the effects of emissions variability in space and time on the concentration predictions from both short-and long-term models, and the resultant required resolution of the emissions parameters.

Transport and Diffusion

The most apparent need here is for further evaluation of the horizontal and vertical dispersion coefficients and their dependence upon meteorological conditions, surface roughness, urban structure, and topography. This can probably best be accomplished through special tests involving inert tracer materials.

Transformations

Clearly this is an area where evaluations of existing formulations are sorely needed. Such evaluations can take the form of either laboratory or atmospheric experiments. If we consider photochemical kinetics mechanisms, virtually all evaluations to date have involved the use of data from laboratory experiments. While this is a necessary step, the atmospheric validation phase must not be neglected if a working atmospheric model is to be achieved. There may well be surprises resulting from atmospheric evaluation efforts, with regard to the operative chemical mechanism, that will feed in directly to the redesign of the laboratory experiments.

Major uncertainties in the area of transformations involve the importance of the following:

(1) gas-to-solid transformations, such as photochemical generation of aerosols and conversion of SO_2 to sulfates, and

(2) effects of turbulent mixing rates on chemical reaction rates.

The latter problem is particularly troublesome, since it involves interactions between the transport and diffusion (meteorological) module and the transformations (chemical) module.

Removal

Surface removal rates (deposition velocities) are not known for any of the major pollutants; these could be significant for those species that react chemically with the surface. For instance, Calder (1972)* has estimated that between 18 and 62 per cent of the total ammonia in a plume is removed after 20 miles of travel over a water surface. The estimates of removal rates that are used in existing models should be measured as part of an evaluation program. Two possible techniques are as follows:

(1) Measure the total pollutant horizontal flux in cross-wind vertical sections of a plume at different downwind distances, and ascribe the difference to ground removal; or

(2) Measure the uptake or surface flux (F) of a pollutant at the surface with, say, a water trap, as well as the average concentration (C) in the air above, and compute the deposition velocity (v_d) from the usual relation $v_d = F/C$.

IV. MODEL VALIDATION ACTIVITIES OF THE U.S. ENVIRONMENTAL PROTECTION AGENCY (EPA)

Efforts are continuing to carry out those calibration and evaluation efforts that are possible through the use of available data. An extensive evaluation program is presently nearing completion in which three photochemical models developed by separate contractors are being jointly tested against a common data base for the Los Angeles Basin, supplied by EPA.

The available data sets, however, are invariably deficient in several important respects, which has seriously hampered most of our evaluation efforts. Mainly for this reason, EPA is planning an extensive multiyear Regional Air Pollution Study (RAPS) in the St. Louis area. The principal objective is the refinement and evaluation of AQS models for general use in determining least-cost air pollution abatement strategies. The details of this field program are still being formulated, but current plans call for a network of 25 to 30 aerometric and meteorological stations, along with supplementary instrumented aircraft and mobile stations to support special experiments. Full operation of the network should be underway by April 1974.*

---

*Calder, K.L., 1972: Absorption of ammonia from atmospheric plumes by natural water surfaces. To be published in Water, Air and Soil Pollution.

In the meantime, other special experiments of a limited nature may be conducted in other appropriate locations, as resources permit, for improvement of certain particularly weak modeling areas, such as in the transpormation and removal modules.

---

*)A more detailed discussion of this program is to be furnished by another paper at this meeting.

Chapter VII

THE U.S. REGIONAL AIR POLLUTION STUDY (RAPS)

by

R. A. McCormick*

ENVIRONMENTAL PROTECTION AGENCY
NATIONAL ENVIRONMENTAL RESEARCH CENTER
DIVISION OF METEOROLOGY
Research Triangle Park, North Carolina 27711

3rd Meeting of Panel on Modeling of the NATO Committee
on the Challenges of Modern Society

Paris, France
October 2-4, 1972

---

*On assignment from National Oceanic and Atmospheric Administration, Department of Commerce

THE U. S. REGIONAL AIR POLLUTION STUDY (RAPS)

The Amendments of 1970 to the Clean Air Act of the United States have required the establishment of national primary and secondary ambient air quality standards and the design of implementation plans to meet those standards.

The Amendments of 1970 clearly presuppose that 'performance' (i.e. emission) standards can be set with respect to achievement of air quality standards either (a) through an appreciation of those physical and chemical factors of transport, dispersion, and transformation within the atmosphere which govern source-receptor relationships being built in the control strategy, or (b) through an accommodation such as 'universal abatement' in which all sources of a pollutant are reduced to the maximum extent possible within the 'state of the art', or to a level (linearly) proportional to the degree of air quality improvement needed to meet standards.

In practice, an expediency of universal abatement can be more readily formulated and applied than strategies which take into account source-receptor relationships through simulation modeling of the atmospheric processes. However, it offers little more than a hope that the desired effect on air quality will be achieved on all significant scales of time and space. Further, the concept is an arbitrary one in that consideration is given neither to the fact that all sources do not contribute to an air pollution problem in proportion to the strength of their emissions, nor to the cost-benefit factors which should be taken into account in a responsible air quality management scheme.

In principle, the deficiencies of the universal abatement concept can be overcome through utilization of simulation modeling techniques in the development of abatement strategies. By this means information can be developed on the costs of control for each source or set of sources for different kinds of abatement practices and for different levels of control. It is possible to identify least cost solutions for existing and possible new air quality standards, and to clarify or delineate the cost-benefit relationships. However, it is recognized that much improvement is needed in the scientific and technical knowledge and capability necessary to confidently relate in an analytical fashion the cause and effect both between emission and air quality and between control strategies and air quality.

There can be no doubt as to the value of such a strategy testing capability. Without it, intelligent direction cannot be given to improving the state of the art of emission control; nor can correct decisions be made between alternatives (a) in control strategies that do not depend on emission suppression, (b) in allocating priorities, and (c) in assisting cost-effectiveness in either case.

It is the goal of the Regional Air Pollution Study (RAPS) to improve the technical and scientific knowledge of atmospheric processes on scales encompassing major urban centers, i.e. 100-150 km to allow the definition of better air quality management schemes than are now possible. More specifically, the objectives are to:

(1) Demonstrate and evaluate how well the effectiveness of air pollution control strategies may be expressed and predicted within air quality control regions.

(2) Provide a scientific basis for developing improved control strategies.

To achieve these objectives, four principal tasks must be accomplished:

- Test, verify, and evaluate the capability of mathematical simulation models to describe and predict the transport, diffusion, and transformation of both inert and reactive pollutants over a regional area.
- Develop an improved understanding of the chemical, physical, and biological processes that are entailed in determing the concentration of pollutants and the modification of air quality.
- Develop a better evaluation of factors of significance to the design of improved control strategies in the urban/rural complex, including economic costs and the role of land use and community planning.
- Develop improved technology that can be applied in local and regional control agency operations, including techniques for emission inventories, air quality and meteorological monitoring, data handling and analysis, and the objective assessment of effectiveness.

It is apparent that to fulfill these tasks requires a concerted, coordinated effort among our workers in many fields of science and technology. The complete work plans of the meteorologists, chemists, economists, engineers, and ecologists are still in the process of formulation from their conceptual status. Only an outline of the meteorological projects will be presented here. A more complete summary of all aspects of RAPS to be pursued will be made available in due course.

METEOROLOGY PROGRAM

As envisioned, the RAPS program activities in physical sciences can be classified into three principal work categories:

I. Evaluation and Improvement of Current Models
II. Development and Validation of New Models as Required and Anticipated.
III. Instrumentation Improvement and Development

In outline, the meteorological studies and experiments are planned to involve the following:

Evaluation of the accuracy of existing models by comparing predictions with air quality data.

a. Probable models that would be evaluated: (CO), (SO_2 and particulates), (photochemical pollutants).
b. All models would have the capability for calculating frequency distributions of hourly averaged concentrations.
c. Spatial averaging of calculated concentrations: 0.5 km (central city), increasing to 10 km (rural areas).
d. Predictions would be compared with observations based upon the same spatial average, obtained by rooftop line-integral measurements over a triangular horizontal path, utilizing mirrors mounted on buildings 0.5 km away from an instrument such as the correlation spectrometer, or a laser device.

e. "Clusters" of three conventional (direct-sampling) analyzers would be mounted at strategic points near mid-paths or above to provide comparison and statistical relationships between point and spatial average types of measurements.

f. If line-integral technique proves not to be feasible, "clusters" of point samplers arranged as in (e) to give a representation of an average concentration over a 0.5 km square would still be used. Three of these clusters would be required: one downtown, one in an industrial area, and one in a commercial-residential area.

g. Rural measurements could be accomplished without clustering of instruments, preferably using two mobile systems, one upwind and one downwind of the city.

h. An appropriate accuracy goal might be 20% RMS error between calculations and observations.

Identification of specific modules responsible for model inaccuracies and make refinements as necessary

a. The basic modules of air quality models relate respectively to emissions, meteorological dispersion, and chemical transformation. Isolating the predictive errors to one or another of these modules is difficult, but this must be done if the model is to be improved.

b. To verify the gross accuracy of the emissions model, vertical line-integral pollutant measurements would be taken around the periphery of the urban area. This would be accomplished with a mobile system, such as a correlation spectrometer. This instrument, however, is only applicable to SO_2 and NO_2 at the present time. Using suitable wind data, these measurements would give the total pollutant quantity emitted from the city. On this basis the emissions model could be checked in a gross fashion. It might be possible to check the modeled spatial emissions distribution by measuring around smaller areas within the city.

c. If the emissions are known to be accurately modeled, then the performance of the meteorological diffusion model can be examined by comparing calculations of CO (or another quasi-inert pollutant) with observations.

d. Errors in calculating reactive pollutant concentrations using a photochemical diffusion model can be isolated to the chemical kinetics module if the model calculates CO correctly.

Develop suitable methods for estimating meteorological inputs for models for applications where detailed data are lacking, or for using air quality models in a predictive mode.

a. This involves suitable characterization of the three-dimensional structure of the urban boundary layer and its relationship to ambient (non-urban) atmospheric conditions and to urban properties. Of basic interest are the principal meteorological inputs to the models: wind speed and direction, atmospheric stability and mixing depth.

b. The model currently being developed under contract would be evaluated for this application by comparing its calculations of the above parameters with observations from an urban meteorological network consisting of the following:

(1) About 10 geometrically located stations having low inertia wind sensors at 30 m; about half would also have thermocouples at 3 and 30 m. This would give the low-level wind field and the stability distribution.

(2) Local wind and temperature soundings by balloon up to once per hour.

(3) Aircraft temperature and turbulence vertical profiles at various points over the city three or four times per day.

(4) Mobile lidar, acdar, radiometer, etc., measurements as appropriate to supplement direct vertical profile measurements. Two lidars could be quite useful in documenting the mixing depth structure over the city.

c. This part of the program should also help determine whether the prediction of urban meteorological fields is feasible, or whether these will always have to be specially measured for each model application.

d. In addition, the meteorological model developed here should permit the extension of air quality modeling into the true fully predictive mode.

Develop improved dispersion formulations, particularly for light-wind conditions

Urgently required although lacking at the present time is an ability to model pollution dispersion in the light-wind conditions that normally characterize air pollution episodes. In addition to theoretical approaches this problem will probably necessitate some special urban tracer tests of the kind mentioned in connection with the boundary layer program that is discussed later in this document.

Develop improved chemical transformation formulations

In addition to the more purely chemical aspects of this problem that would be a prime responsibility of the Division of Chemistry and Physics. of Environmental Protection Agency, it is now apparent that the normal laboratory chemical kinetic will require some major modifications when the reactions occur in the turbulent urban atmosphere. This will require a comprehensive synthesis of considerations of pur kinetics with concepts from atmospheric fluid dynamics. In addition, special atmospheric experiments may also be required by marking air parcels with tetroons and then monitoring the chemical properties of the moving parcel in a Lagrangian fashion by using an instrumented helicopter or blimp.

Develop improved formulations for characterizing pollution removal processes in the atmosphere

Direct determination of atmospheric removal rates downwind of a city should be possible by means of aircraft mapping of vertical cross-wind sections of concentration at various downwind distances. Laboratory studies are also expected to furnish valuable information.

Exercise developed models and optimize users' versions to facilitate applications

This will require simulated control strategy exercises. It may also be possible to arrange real exercises in which emissions are controlled and the resulting air quality is measured. This would provide a real test of the capabilities of the models. The models would also be applied to local plans for new highways, industrial complexes, etc. In this way experience with the models as tools would be developed, which would then be applied to refine the models in the users' sense. Considerable importance is attached to the development for operational use of appropriate simplified versions of sophisticated models.

Boundary Layers Studies

Determine the detailed wind and temperature structure of the boundary layer.

a. A network of fixed sites will be operated to obtain continuous records of wind, pressure, and temperature, to relate the surface air flow, and its spatial and temporal variations to the mesoscale pressure and thermal gradients. Wind will be measured at about 12 well exposed sites distributed over a radius of about 20 km, whereas pressure and temperature will be measured at one central site, and four outlying sites each on the order of 40 km from the central site. All sites will, if possible, be on a locally elevated topographic feature in order to avoid "contamination" by local cool air drainage, but all sites should be at the same elevation, if possible.

b. In addition, a denser network of near-surface temperature measurements will be set up to cover about the same area as the wind measurements. The purpose of this network will be to document the urban heat island, and it will be laid out in a strongly non-uniform distribution to concentrate measurements where the surface temperature gradients are concentrated. Up to 25 additional sites will be included in this network, with provisions for relocation of portions of the network after 1/2 to 1 year of data collection to document various other aspects of the temperature field.

c. Measurements of wind and temperature should be made at several levels on tall (>150 m) towers, preferrably at a minimum of two sites, to obtain the vertical variation of these parameters. Bivanes should be mounted at two levels, with routine measurements of the gross high- and low-frequency standard deviations of velocity fluctuations. Vertical profiles of wind and temperature through a depth of about 3 km should be measured at least 3 times daily. It is hoped that indirect techniques can replace the usual radiosonde for these measurements.

d. It is expected that the majority of sites for the above measurements can be co-located with the air quality sites, and the data collection and processing would use the same central computer facilities. Batches of data would be analyzed as they accumulate, to obtain intercorrelations between parameters, and to specify the measured features of the air flow as functions of the forcing by large scale synoptic weather sequences and net radiant fluxes.

e. To supplement the data from fixed networks temperature surveys using vehicle-mounted air temperature sensors would be conducted under a variety of weather conditions. These would more thoroughly map the near-surface temperature field and permit more valid interpretation of the data from the fixed network.

Determine the energy balance of the urban boundary layer and its radiational properties.

a. A series of experiments will be conducted to simultaneously measure all components of the heat flux under a variety of weather conditions. Sensible heat flux can be measured by both fixed and aircraft-mounted sensors, components of the short-and long-wave radiant heat flux would be measured using the same mix of sensors, artificial heat generation would be adapted from the emission inventories, and estimates of ground heat storage would be obtained on a best-effort basis. Detailed temperature and humidity profile from aircraft would be required along with a lesser number of wind profiles, to evaluate the horizontal advection and air storage terms of the heat balance. These experiments would yield detailed information on the variation in depth of urban boundary layer, which would be supplemented, both during experimental periods and on a semi-routine scheduled basis, by Lidar surveys of the aerosol envelope over the area.

b. An important factor in the radiation budget for polluted urban atmospheres is believed to be the scattering of radiation by atmospheric aerosol. Regular air quality observations of the RAPS study should be augmented by special aerosol and light scattering measurements. Lidar techniques will be used to provide low-level vertical profiles of aerosol distribution as a basis for theoretical estimation of radiation scattering effects. In addition, long-wave spectrometer observations will be used to estimate radiation from gaseous pollutants.

c. Data on the short-wave (U.V.) radiation in the urban boundary layer, and particularly when this is polluted, is also required for quantitative understanding of the photochemical pollution problem. Satisfactory specification of the three-dimensional U.V. field will probably require aircraft observations.

Determine by tracer experiments dispersion characteristics for short and medium distances.

A variety of tracer experiments will be included, using as many proven tracer systems and substances as are available simultaneously. Sampling will depend on the tracer release mode and on the meteorological conditions, and should include, in addition to fixed and mobile surface samples, aircraft sampling through the depth of the convective layer in the daytime, supplemented by elevated but ground-based sampling at night. Most daytime tracer releases should be a line-source release from an aircraft, whereas the nighttime releases should be point-source releases at varying elevations and locations within the urban area. Analyses of the results would be directly applicable in dispersion formulations, but data should be further analyzed, together with the meteorological data, to determine where, in three dimensions, the air goes under various conditions. In particular, the reality and dimensions of Clarke's urban heat plume should be defined. Special tracer tests will be required to characterize dispersion under the light wind conditions that frequently occur with air pollution episodes.

Determine various characteristics of the long-range transport of pollutants.

a. A basic need for a global or large-scale modeling of pollutant transport is for improved understanding of atmospheric dispersion beyond the immediate vicinity of metropolitan sources, such as is involved, for instance, in the acid precipitation phenomenon of northern Europe. Long-range transport also becomes important in considering interurban and regional transport. This task would investigate many aspects of the problem, initially for aerosols, SO_x and NO_x, including deposition or absorption effects at the earth's surface and the effects of precipitation in removing pollution from the earth's atmosphere.

b. Comprehensive emission inventory and ground-based air quality data for the urban area will be supplemented by rural surface-based air quality measurements and helicopter and aircraft measurements upwind, over, and downwind of the city. The analyses will be based largely upon determination of pollution budgets.

c. In addition to the direct approach, it will be necessary to obtain special data on long-range dispersion by tracer experiments.

Investigate effects of urban waste heat emission on regional climate.

a. The continuing rapid transition of rural areas to urban use and the rapid increase in consumption of energy has created serious concern about the dissipation of urban heat waste and its effects on regional climate and urban populations. In some large cities, the waste energy dissipated per unit area as heat during the winter season, is even now greater than the energy received from the sun. By the year 2000, effects of the surface fabric and heat emission from "regional cities" in the Northeast U.S.A. could be profound and extend far beyond an urban source. Dispersion processes for regional cities could also be very different from those occurring with smaller cities.

b. Land use and waste heat emission inventories obtained during the RAPS study will be used with detailed measurements of the horizontal temperature field obtained from mobile surface and airborne (infrared skin temperature) sensors to establish the present urban thermal environment in St. Louis. These data will be compared with extensive historical data obtained in St. Louis nearly two decades ago in order to determine effects of changing land use and energy consumption patterns on the thermal environment of the city.

c. Temperature probes implanted in urban structures will measure the time variation as a function of meteorological conditions of the flow and storage of thermal energy. Such data will be used to develop models that predict the consequences of increasing heat pollution and to determine optimum means for alleviating the problem.

RESOURCE ESTIMATES

In total it is anticipated that the initial RAPS project, to be conducted initially in St. Louis, Missouri, will take about 5 years and cost on the order of 25 million dollars. On the order of 40 to 50 man years, per year, of scientific and technical personnel will be required. Before the work in St. Louis is completed, however, it is expected that additional cities will be chosen for similar studies, but on a reduced scale. The object will be to test the generality of the results obtained in St. Louis and verify criteria developed for minimum routine observational data necessary to keep the models validated.

Other aerometric studies sponsored by Federal agencies are also in progress in St. Louis for which EPA has been designated as the lead agency. These studies are known as METROMEX (Metropolitan Meteorological Experiment), and FAPS (Fate of Pollutants Study). The former program, an investigation of inadvertent weather modification from urban-related factors, has been described in the Bulletin of the American Meteorological Society, p. 958, Oct. 1971. The FAPS project is being undertaken by scientists of the National Center for Atmospheric Research (NCAR) and is concerned with the history and fate of pollutants downwind from St. Louis and their impact on the regional environment.

Chapter VIII

AN EVALUATION OF SOME CLIMATOLOGICAL DISPERSION MODELS

by

D. Bruce Turner*, John R. Zimmerman*, and Adrian D. Busse*

ENVIRONMENTAL PROTECTION AGENCY
NATIONAL ENVIRONMENTAL RESEARCH CENTER
DIVISION OF METEOROLOGY
Research Triangle Park, North Carolina 27711

3rd Meeting of Panel on Modeling of NATO Committee

on the Challenges of Modern Society

Paris, France
October 2-4, 1972

---

*On Assignment from the National Oceanic and Atmospheric Administration, Department of Commerce

VIII-2

AN EVALUATION OF SOME CLIMATOLOGICAL DISPERSION MODELS

by

D. Bruce Turner*, John R. Zimmerman*, and Adrian D. Busse*

ABSTRACT

Six different dispersion models were used in a climatological mode of application with point source and area emission data to calculate annual (1969) sulfur dioxide and total suspended particulate matter for the New York Air Quality Control Region. Two of the models, the Air Quality Display Model and the Climatological Dispersion Model, use joint frequency distributions of wind direction, wind speed, and stability class as meteorological data. The Climatological Dispersion Model (single stability) requires only a wind direction frequency and harmonic mean speed for each direction. The other three models: Gifford '72, Modified Hanna, and Modified Hanna Including Source Height; require only mean annual wind speeds for climatological application.

Simple models are as highly correlated with measurements as are the more complex models, explaining 70% of the sulfur dioxide variance and 40% of the particulate variance. For SO_2, root mean square errors for the best complex model are 52; those for the simple models are 56 to 59. The standard deviation of the measurements is 72. For particulates, root mean square errors for the complex model are 16; those for the simple models are 19 to 40. The standard deviation of the measurements is 23.

It is difficult to achieve results surpassing those of the simple models. Of the two more complex models, the AQDM and the CDM, the CDM yields smaller errors with means and maxima nearer those of the measurements. Evaluation of models should include comparison of results with those from simple models applied to the same data.

---

*On Assignment from the National Oceanic and Atmospheric Administration, Department of Commerce

INTRODUCTION

Six different dispersion models were used to calculate annual (1969) sulfur dioxide and total suspended particulate matter for the New York Air Quality Control Region. Two of the models, the Air Quality Display Model and the Climatological Dispersion Model, use joint frequency distributions of wind direction, wind speed, and stability, as meteorological data. The Climatological Dispersion Model applied for a single stability requires only a wind direction frequency and harmonic mean speed for each direction. The other three models based upon ideas of Gifford and Hanna (1971, 1972) require only mean annual wind speeds for climatological application. These are referred to as: Gifford '72, Modified Hanna, and Modified Hanna Including Source Height.

The emission inventory, measured air quality data, meteorological data, and climatological estimates of pollution concentration using the Air Quality Display Model were obtained from EPA's Air Quality Management Branch. Emission estimates for 1969 for both pollutants for 854 area sources varying in size from 1 km^2 to 100 km^2, and for 674 point sources were included. Estimates of stack height, stack diameter, stack gas exit velocity, and stack gas temperature were also included for the point sources. A stability wind rose (joint frequency distribution of wind direction, wind speed, and stability class) was available for La Guardia Airport based on the 3-hourly observations during 1969. These observations are routinely available in computer compatible form (punch cards or magnetic tape).

Each of the models was used to calculate mean annual concentrations of sulfur dioxide at 75 locations and total suspended particulate matter at 113 locations. These estimates were compared with mean annual concentrations based upon measurements.

DESCRIPTION OF MODELS

1. Air Quality Display Model (AQDM)

The AQDM, a climatological model based on ideas of Martin and Tikvart (TRW Systems Group, 1969; Martin and Tikvart, 1968; and Martin, 1971), considers the joint frequency distribution of wind direction to 16 points, wind speed in 6 classes, and stability categories in 5 classes. Computations for a receptor point are made by considering the contribution of each point and area source to this receptor. Separate calculations are made for each speed class - stability class combination for the wind direction sector about the receptor that contains the source. For area sources a modification of the virtual point source method is used. Estimation of area source heights are assumed to be effective height of the area source. The effective height can be different for each area source. Holland's plume rise equation (Holland, 1953) is used to estimate the effective height of point sources. A feature of the AQDM is that a source contribution file consisting of the partial concentration of each receptor due to each point and area source is retained at the end of the computation. This is primarily used as input to control strategy studies.

2. Climatological Dispersion Model (CDM)

The CDM described in detail by K. L. Calder (1971) has been applied to air quality estimates for Ankara, Turkey, and St. Louis (Zimmerman, 1971, 1972) for the Committee on Challenges of Modern Society. Although similar in many respects to the AQDM, the CDM contains several distinct features. In the CDM, area sources are calculated using the narrow plume hypothesis (Gifford and Hanna, 1971) applied for winds within a sector (Calder, 1971) which involves an upwind integration over the area sources. Emission rates at various upwind distances, using an expanding scale, are averaged over an arc within the sector. A power law for the vertical wind profile which is a function of stability is used to extrapolate surface winds to the source height. Estimation of effective height of point sources is by Briggs plume rise (Briggs, 1969). The total concentration at each receptor is the sum of 32 concentrations. These concentrations are those from point and from area sources for each of the 16 wind directions. These values are retained and are useful in plotting direction contribution pollution roses. The running time of the CDM is about 73% of that required by the AQDM.

3. Climatological Dispersion Model (Single Stability)

Whereas both the AQDM and the CDM are applied for 5 different stabilities and 6 wind speed classes within each stability class, this model performs the calculations for a single stability and further reduces the computations by using a single wind speed for each of the 16 wind direction sectors. The single wind speed is a harmonic mean of the average speed for each wind speed class weighted for its frequency. The running time of this single stability version of the CDM is about 30% of that required by the CDM.

4. Gifford '72

Drs. Frank Gifford and Steve Hanna of NOAA's Atmospheric Turbulence and Diffusion Laboratory in Oak Ridge, Tennessee, have been active in developing simple dispersion models for estimating concentrations (Gifford and Hanna, 1971; Hanna, 1971). In a recent manuscript (Gifford and Hanna, 1972), they have suggested use of

$$\chi_A = C \frac{\bar{q}}{\bar{u}} \qquad (1)$$

where χ_A is the concentration in $\mu g m^{-3}$ of the pollutant of interest due to all area sources for a particular averaging time, C is a dimensionless constant, $\bar{q}$ is an average area emission rate in $\mu g m^{-2} sec^{-1}$ in the vicinity of the receptor, and $\bar{u}$ is the mean wind speed in m sec^{-1}. Both $\bar{q}$ and $\bar{u}$ are for the same averaging time as the concentration, χ_A. They suggest that the values of C are 50 for sulfur dioxide and 225 for particulate matter. Concentrations at this receptor from point sources for the same averaging time should be added to the concentrations from area sources. These can be determined from an appropriate point source model. Without firm direction from the manuscript of Gifford and Hanna as to what area about the receptor should be used to obtain average area emissions, the authors selected an area after an investigation which will be described later.

5. and 6. Modified Hanna

Since emissions close to a receptor at about the same height as the receptor have a greater influence than emissions at greater distances, it was felt that an improvement to the above Gifford '72 model could be made which would eliminate the use of the rather arbitrary constant C, and would also eliminate the difficulty of not knowing just which area should be considered in determination of the average area emission rate. The model can be expressed as:

$$\chi_A = \frac{1}{\bar{u}} \sum_i k_i \bar{q}_i + b \qquad (2)$$

where i is an index referring to a range of distances from the receptor, $\bar{q}_i$ is the average area emission rate for this range of distance about the receptor, $\bar{u}$ is mean wind speed as before, b is background concentration of the pollutant considered beyond the last distance considered in the summation, and the coefficient, k, is determined from:

$$k_i = \int_{x_l}^{x_u} \frac{2}{\sqrt{2\pi}\,\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] dx \qquad (3)$$

where x_l and x_u are the lower and upper limits of distance of the i^{th} range, σ_z is a dispersion parameter dependent upon distance and representative of mean stability conditions for the period of interest, H is a single effective height of emission for the pollutant considered for area sources in the region under consideration. In general, the value of b will be the concentration of the particular pollutant at the boundaries of the region considered, i.e., the boundary of the emission inventory. Note that the k's are dependent only upon the mean meteorological conditions and the height of emission and, therefore will be constant for a given distance range, and independent of receptor location. On the other hand, the $\overline{q_i}$'s are determined for different distance ranges about each receptor and, therefore, are dependent upon receptor location.

Model 5, referred to as the Modified Hanna, is applied with H=0. This is the same in concept as that of Steve Hanna (1971). The only difference is that in this model sources are considered for ranges of distance without regard to direction variations. For this model the values of k can be determined analytically.

Model 6, referred to as the Modified Hanna Including Source Height, uses a mean value of effective height of emission for each pollutant. For this case the values of k are determined by numerical integration.

Both Models 5 and 6 can be considered as further simplifications to the CDM and CDM (single stability) models since another liberty has been taken, that of calculating emissions for various distance ranges instead of in each wind direction sector.

APPLICATION OF THE MODELS TO THE NEW YORK REGION

With each of the models, calculations of ground level concentrations of both sulfur dioxide and total suspended particulate matter were made. Measurements of sulfur dioxide were available at 75 locations and of particulate matter at 113 locations.

As indicated, the AQDM was applied to the data for this area by the Air Quality Management Branch. A background of 35 μgm^{-3} was added to each calculated value of particulate concentration before comparing with measurements. A background of 35 was also added to each calculated value of particulate matter by the CDM before comparing with the measurements.

For applying the CDM for a single stability, Table 1 lists the frequencies and the harmonic mean wind speeds for each direction. The model was applied for three different single stabilities. The values used for the σ_z parameter most closely approximate those corresponding

TABLE 1

Frequencies and Harmonic Mean Wind Speeds for Each Direction

SECTOR	$f(\theta)$	$\bar{u}(\theta)$ ($m\ sec^{-1}$)
NNE	0.088	3.65
NE	0.054	2.98
ENE	0.076	3.27
E	0.084	3.53
ESE	0.036	2.82
SE	0.010	2.04
SSE	0.014	2.78
S	0.025	3.54
SSW	0.117	4.00
SW	0.044	2.93
WSW	0.062	3.27
W	0.075	3.72
WNW	0.071	4.73
NW	0.086	4.43
NNW	0.082	3.90
N	0.075	4.12

TABLE 2

Dispersion Parameter Coefficients and Exponents

$$\sigma_z = a\,x^b$$

Range of x (meters)	C Stability a	C Stability b	C/D Stability a	C/D Stability b	D Stability a	D Stability b
<500	0.1120	0.9100	0.1078	0.87645	0.0856	0.8650
500-5000	0.1014	0.9260	0.1725	0.80072	0.2591	0.6869
>5000	0.1154	0.9109	0.3546	0.71611	0.7368	0.5642

to Pasquill's C, D, and something between C and D (Pasquill, 1962; Turner, 1967) so the notation: C, D, C/D is used to designate these. The coefficients and exponents for various downwind distances from the source, x, for these three stabilities used to determine σ_z from:

$$\sigma_z = ax^b \qquad (4)$$

are given in Table 2.

For application of the Gifford '72 model, the mean wind speed for La Guardia Airport for the year 1969 as given by the Local Climatological Data (Environmental Science Service Administration, 1969) of 11.6 miles per hour (5.1852 m sec^{-1}) was used. As indicated, Gifford (1972) is not clear as to the size of the area that should be considered for averaging area emission rates. Therefore, three distances were selected: 3, 5, and 10 km. Using the emission rates for the area sources on the 1 km basis previously prepared as part of the CDM run, a computer calculation was made to determine average emissions for both SO_2 and particulate within circles centered on each receptor for radii corresponding to the three above-mentioned distances. If the center of a 1 km source square was within the circle, it was included in the averaging; if the center was outside, it was not included. After determining [illegible] average emission rate for the three different radius circles, the linear correlation coefficient of measurements of concentration as a function of average emission rate was determined for both pollutants. This appears on the left side of Table 3. From these results, the average emission rates for circles with a radius of 10 km were selected for use in applying the Gifford '72 model. At a later time the average emissions for larger circles and the corresponding correlation coefficients were determined. These appear in the right hand portion of Table 3.

Since Gifford indicates that the values of the factor C of 50 for sulfur dioxide and 225 for particulate matter were determined without consideration of any background values, no background was added to the estimates from this model before comparing with measurements. Comparisons of this model were made with measurements for both: estimates from area sources only, and estimates from the area sources using this model with estimates of concentration due to point sources as determined from the CDM model added to the area estimates. (After noting the results achieved with this model, a background of 35 was added for particulate matter estimates for an additional comparison.)

In applying the Modified Hanna Model to this region, six ranges of distances were used as shown in Table 4. From intermediate results punched on cards during the determination of the average emission rates for various sized circles, it was simple to determine the average emission rates for the 5 annular areas. For application of the Modified Hanna Including Source Height (Model 6), the average emission heights

TABLE 3

Linear Correlation Coefficients of Measured Air Quality Data with Average Emission Rate of Circles of Given Radius about Each Receptor

Pollutant	Number of Receptors	Radius of Emission Area (km) 3	5	10	20	30	40
Sulfur dioxide	75	0.73	0.79	0.81	0.85	0.78	0.70
Particulate matter	113	0.61	0.64	0.63	0.63	0.63	0.60

TABLE 4

Limits of Integration and Corresponding Values of k from Equation (3)

i	x_l km	x_u km	k_i		
			Model 5	Model 6	
			H = 0	H = 10 Particulate	H = 30 SO_2
1	0	3	163.468	50.331	30.715
2	3	5	12.264	12.133	11.844
3	5	10	19.344	19.183	18.993
4	10	20	23.551	23.053	22.973
5	20	30	16.085	15.580	15.555
6	30	40	12.589	12.120	12.110

of 30 meters for sulfur dioxide and 10 meters for particulate matter were chosen as representative of effective heights of emission for the New York region. (One could apply this model using different effective heights of emission for various receptor locations, but only one height for each pollutant was used here.) Using values of the dispersion parameter, σ_z, corresponding to C/D stability the k_i's were determined by integrating analytically over appropriate distance ranges for use in Model 5 and using the σ_z's for C/D stability and the above emission heights, numerical integrations were performed to determine the values of the factors, k_i for use with Model 6. These are also shown in Table 4. Values of background concentration, b, of 0 and 35 were used for sulfur dioxide and particulate matter respectively in equation (2).

STATISTICS USED FOR EVALUATION

To evaluate the various models, 12 different statistics were used. One of these was the mean concentration for all stations. Considering the error for each location to be defined as the calculated concentration from the model minus the measured concentration, the root mean square error and the mean absolute error were determined. As an indication of the range of errors at the individual measurement locations, the largest negative error (underestimate), the largest positive error (overestimate), and the range of errors (the largest positive error minus the largest negative error) were tabulated. Linear correlation coefficients, the variance of the correlation (the square of the correlation coefficient) and the slope and intercept of the least squares line of regression between model estimates and the measured values were also calculated.

Because of its importance to the meeting of air quality standards, the error at the location with the highest measured concentration is of interest as well as the maximum estimated concentration at any of the measuring station locations.

RESULTS

The results of the comparison of model estimates with measurements are given in Table 5 for sulfur dioxide and in Table 6 for particulates. In addition to comparing the calculated AQDM estimates with measurements, the Air Quality Management Branch had used the measured air quality data to calibrate the AQDM. Considering the calculations without background as the independent variable, the measurements as the dependent variable, least square lines that are forced to have an intercept of 0 for sulfur dioxide and 35 for particulate matter were determined. The slope and intercepts for these lines are given in Table 7. Using the equations of these lines, "calibrated" concentration estimates were determined from the calculated concentrations. This was done similarly for all other models. The comparisons of these estimates with the

TABLE 5. NEW YORK - SULFUR DIOXIDE

MAX MEAS = 350

	MEAN (MEAS =135)	NUMBER	RMSE (STD DEV OF MEAS =72)	MEAN ABSOLUTE ERROR	LARGEST NEGATIVE ERROR	LARGEST POSITIVE ERROR	ERROR RANGE	LINEAR CORREL. WITH MEAS.	VARIANCE	SLOPE	INTERCEPT	ERROR AT POINT OF MAXIMUM MEAS.	MAXIMUM ESTIMATED CONC. AT A MEAS. POINT
1 AIR QUALITY DISPLAY MODEL (AQDM)	211 (116)	75 (75)	121 (37)	92 (28)	-87 (-117)	310 (74)	397 (191)	0.89 (0.89)	0.79 (0.79)	0.45 (0.82)	31 (31)	112 (-97)	566 (310)
2 CLIMATOLOGICAL DISPERSION MODEL (CDM)	138 (115)	75 (75)	52 (44)	37 (32)	-118 (-143)	166 (121)	284 (264)	0.84 (0.84)	0.70 (0.70)	0.66 (0.79)	35 (35)	-101 (-143)	368 (307)
3 CDM (SINGLE STABILITY)													
3A CDM (D STABILITY)	206 (112)	75 (75)	124 (45)	89 * (33)	-112 (-153)	332 (114)	444 (267)	0.84 (0.84)	0.71 (0.71)	0.41 (0.76)	40 (40)	13 (-153)	577 (313)
3B CDM (C STABILITY)	94 (101)	75 (75)	56 (55)	46 (45)	-128 (-122)	96 (118)	224 (240)	0.82 (0.82)	0.67 (0.67)	0.73 (0.68)	56 (56)	-119 (-101)	307 (329)
3C CDM (C/D STABILITY)	139 (107)	75 (75)	64 (49)	45 (39)	-115 (-125)	188 (109)	303 (234)	0.84 (0.84)	0.70 (0.71)	0.55 (0.72)	49 (48)	-56 (-125)	423 (324)
4 GIFFORD '72													
4A AREA ONLY	54 (91)	75 (75)	82 (63)	72 (54)	-175 (-151)	29 (125)	204 (276)	0.81 (0.81)	0.66 (0.66)	1.07 (0.63)	67 (67)	-175 (-54)	180 (304)
4B WITH CDM POINT ESTIMATES	79 (107)	75 (75)	59 (48)	50 (38)	-137 (-118)	49 (115)	186 (233)	0.85 (0.85)	0.72 (0.72)	0.97 (0.72)	48 (48)	-137 (-64)	219 (294)
5 MODIFIED HANNA													
5A AREA ONLY	279 (77)	75 (75)	330 (77)	178 (65)	-145 (-152)	1232 (188)	1377 (340)	0.77 (0.77)	0.60 (0.60)	0.16 (0.58)	80 (80)	1153 (63)	1503 (413)
5B WITH CDM POINT ESTIMATES	305 (81)	75 (75)	348 (73)	193 (61)	-120 (-145)	1270 (189)	1390 (334)	0.78 (0.78)	0.62 (0.62)	0.16 (0.60)	76 (76)	1191 (62)	1541 (412)
6 MODIFIED HANNA INCL. SOURCE HEIGHT													
6A AREA ONLY	102 (96)	75 (75)	58 (57)	45 (46)	-151 (-151)	198 (178)	341 (321)	0.84 (0.84)	0.71 (0.71)	0.62 (0.66)	62 (62)	49 (26)	399 (376)
6B WITH CDM POINT ESTIMATES	127 (105)	75 (75)	56 (48)	38 (37)	-126 (-131)	225 (157)	351 (208)	0.86 (0.86)	0.74 (0.74)	0.59 (0.71)	50 (50)	87 (11)	437 (361)

TABLE 6. NEW YORK - PARTICULATE MATTER

MAX MEAS = 169

	MEAN (MEAS = 82)	NUMBER	RMSE (STD DEV OF MEAS =23)	MEAN ABSOLUTE ERROR	LARGEST NEGATIVE ERROR	LARGEST POSITIVE ERROR	ERROR RANGE	LINEAR CORREL. WITH MEAS.	VARIANCE	SLOPE	INTERCEPT	ERROR AT POINT OF MAXIMUM MEAS.	MAXIMUM ESTIMATED CONC. AT A MEAS. POINT
1 AIR QUALITY DISPLAY MODEL (AQDM)	102 (77)	113 (113)	36 (21)	28 (15)	-51 (-60)	115 (54)	166 (114)	0.62 (0.63)	0.39 (0.39)	0.38 (0.62)	43 (34)	5 (-48)	199 (136)
2 CLIMATOLOGICAL DISPERSION MODEL (CDM)	74 (76)	113 (113)	22 (22)	16 (15)	-63 (-62)	68 (74)	131 (136)	0.61 (0.61)	0.37 (0.37)	0.63 (0.59)	35 (37)	-48 (-43)	135 (141)
3 CDM (SINGLE STABILITY) 3A CDM (D STABILITY)	88 (74)	113 (113)	28 (22)	21 (17)	-80 (-67)	98 (65)	158 (132)	0.64 (0.64)	0.41 (0.40)	0.42 (0.57)	45 (40)	-6 (-39)	165 (132)
3B CDM (C STABILITY)	58 (69)	113 (113)	31 (28)	26 (21)	-78 (-74)	59 (104)	137 (178)	0.57 (0.57)	0.32 (0.32)	0.69 (0.46)	42 (50)	-71 (-40)	126 (171)
3C CDM (C/D STABILITY)	69 (71)	113 (113)	25 (25)	19 (19)	-73 (-72)	75 (82)	148 (154)	0.61 (0.61)	0.37 (0.37)	0.54 (0.50)	45 (46)	-43 (-37)	142 (149)
4 GIFFORD '72 4A AREA ONLY	40 (64) [75]	113 (113) [113]	53 (30) [33]	47 (24) [27]	-117 (-83) [-82]	46 (42) [81]	163 (125) [163]	0.63 (0.63) [0.63]	0.40 (0.40) [0.40]	0.35 (0.47) [0.35]	68 (51) [56]	-56 (-50) [-21]	151 (147) [186]
4B WITH CDM POINT ESTIMATES	51 (68) [86]	113 (113) [113]	47 (27) [36]	40 (21) [28]	-111 (-79) [-76]	59 (38) [94]	170 (117) [170]	0.63 (0.63) [0.63]	0.40 (0.40) [0.40]	0.32 (0.49) [0.32]	65 (48) [54]	-44 (-52) [-9]	164 (143) [199]
5 MODIFIED HANNA 5A AREA ONLY	80 (62)	113 (113)	41 (31)	30 (25)	-77 (-81)	177 (80)	254 (161)	0.64 (0.64)	0.40 (0.40)	0.28 (0.47)	59 (53)	61 (-16)	281 (184)
5B WITH CDM POINT ESTIMATES	92 (66)	113 (113)	45 (28)	32 (22)	-71 (-78)	190 (74)	261 (152)	0.64 (0.64)	0.40 (0.40)	0.27 (0.48)	57 (50)	73 (-20)	294 (178)
6 MODIFIED HANNA INCL. SOURCE HEIGHT 6A AREA ONLY	56 (66)	113 (113)	31 (28)	26 (22)	-80 (-77)	25 (68)	105 (145)	0.66 (0.66)	0.43 (0.43)	0.72 (0.49)	41 (49)	-58 (-23)	129 (172)
6B WITH CDM POINT ESTIMATES	67 (73)	113 (113)	25 (24)	19 (18)	-71 (-69)	37 (55)	108 (124)	0.62 (0.62)	0.39 (0.39)	0.63 (0.54)	39 (42)	-53 (-39)	141 (159)

TABLE 7

Equations of Least Squares Lines (y=a+bx) Used to Determine Calibrated Concentrations

Model	Sulfur Dioxide		Particulate Matter	
	b	a	b	a
1. AQDM	0.5478	0	0.6162	35
2. CDM	0.8330	0	1.0630	35
3a. CDM (D Stability)	0.5429	0	0.7452	35
3b. CDM (C Stability)	1.0790	0	1.4956	35
3c. CDM (C/D Stability)	0.7653	0	1.0637	35
4. Gifford '72				
A. Area only	1.6909	0	0.7430	35
B. With CDM point estimates	1.3435	0	0.6557	35
5. Modified Hanna				
A. Area only	0.2746	0	0.6063	35
B. With CDM point estimates	0.2676	0	0.5512	35
6. Modified Hanna Including Source Height				
A. Area only	0.9435	0	1.4594	35
B. With CDM point estimates	0.8265	0	1.1717	35

measured concentrations are reported in Tables 5 and 6 in parentheses with each model. Note that the "calibrated" estimates are compared with the same measurements used for determining the calibration equations, not with independent data. Although the development of the coefficients for the Gifford '72 should not require the addition of a background concentration, the estimated values from this model were also tested after adding a background of 35 μgm^{-3} to the particulate values. These results are reported in brackets in Table 6.

Models 1 and 2 (both AQDM and CDM) each require joint frequency distributions of wind direction, wind speed, and stability. For the CDM (single stability) only the frequency and mean speed for each direction (Table 1) are required. For the last three models only the mean annual wind speed is used although the effects of the point sources, that are added in, have used the joint frequency distribution information.

Considering first the results for sulfur dioxide, for the mean concentration for the 75 locations, Model 2 with 138, Model 3c with 139, and Model 6 b. with 127 are all close to the mean of measurements of 135 μgm^{-3}. Note that calibration causes all models to underestimate the mean. For the root mean square error, Model 2 with 52, Models 3b and 6b with 56 are examples. Six of the 11 models have a RMSE less than the standard deviation of the measured values, 72 μgm^{-3}.

As expected, calibration reduces the root mean square error but in some cases only slightly. The smallest mean absolute errors are from Model 2 with 37 and Model 6 b with 38. Calibration reduces the mean absolute error. The range of errors is lowest, 186 (-131 to 49), for Model 4 b. Note that all correlations are quite close, ranging from 0.77 to 0.89. The error at the point of the maximum measurement varies from an underestimate of 175 μgm^{-3} to an overestimate of 112 μgm^{-3}, ignoring the huge overestimates of Model 5. Model 3 a. with an overestimate of 13 μgm^{-3} has the least error. Calibration causes Model 6 b's overestimate of 11 μgm^{-3} to be smallest. The maximum estimated concentration at a measurement point ranges from 180 μgm^{-3} to 577 μgm^{-3} (again ignoring Model 5) with Model 2's estimate of 368 closest to the measured maximum of 350 μgm^{-3}. Calibration improves some estimates of the max, notably Model 6 b. with 361.

In the results for the particulate matter (Table 6) for the mean concentration, the 80 μgm^{-3} from Model 5 a is closest to the mean of all measurements of 82. Models 3a, 2, and 5b also are close. Calibration improves the means from most of the models. For the root mean square error, only Model 2 with 21 is less than the standard deviation of measured particulate values of 23 μgm^{-3}. With calibration, Models 1, 2, and 3a have RSME less than 23. For the mean absolute error, Model 2 with 16 μgm^{-3} is the smallest. With regard to the largest errors, the models are not greatly different if Model 5 is excluded. Model 2 has the smallest error range, 131. Generally calibration doesn't have too much effect on the range of errors. The correlations are not greatly different for the various models ranging from 0.57 to 0.66 although they are poorer than those for SO_2. The variance is about half those for SO_2: 0.32 to 0.43 for particulate, 0.60 to 0.79 for SO_2. This may be due, in part, to the difficulty in obtaining a reliable emission inventory for particulate matter and in obtaining representative measurements. The error at the point of maximum concentration is a slight overestimate of 5 μgm^{-3} for Model 1 and a slight underestimate of 6 μgm^{-3} for Model 3a. For the maximum concentration at any measurement point, Model 3a with 165 and Model 4b. with 164 are near the maximum measured at any sampling station of 169. Generally, calibration does not greatly improve the estimate of the maximum. An exception is Model 3b. whose calibrated maximum is 171.

CONCLUSIONS

There is no one model that is superior in all statistics. The AQDM (Model 1) overestimates concentrations. Although we feel that the use of the Holland plume rise equation contributes to this overestimation, it is not the only cause. Many measurements of air quality are needed in order to calibrate the AQDM. This results in a low error but also, in this case, results in underestimated c[illegible]trations for both the mean and the maximum.

The CDM (Model 2) gives a good estimate of the mean and maximum for SO_2 in this test, but somewhat underestimates the particulate concentrations, particularly the maximum. It should be noted that this is without a calibration, therefore no extensive measurement network was required to obtain the result.

The CDM (single stability) with the dispersion parameters given by the C - D stability class (model 3c) gives a better estimate of the mean of all stations than of the other statistics. The errors are somewhat larger than the full model. Like the CDM Model, the CDM (C/D stability) overestimates the SO_2 maximum concentration but underestimates the particulate concentration

The Gifford '72 Model underestimates both the mean concentrations and also the maximum SO_2 but produces a good estimate of the particulate maximum for this test region. Although the errors are somewhat larger than with the other models, they are not greatly different considering the degree of simplicity of this model over the preceding ones. The addition of a background of 35 μgm^{-3} for the particulate estimates improves the results of this model in most statistics with the exception of the maximum concentration at any measurement point.

The Modified Hanna Including Source Height seems to be an improvement over the Gifford '72 Model with regard to means and errors but does not perform as well on the maxima, overestimating SO_2 and underestimating particulate. Note that there is a relatively close correspondence between the CDM (C/D stability) and Model 6b in nearly all statistics and for both pollutants.

Simple models using only mean annual wind speeds and emissions do quite well compared to the more complex models. The input and the calculations are simple. They do have limitations when trying to use the results to apply control strategies. For the simple models at each receptor there are two concentration estimates available: that due to point sources and that due to area sources. Of the more complex models (1 and 2), these data indicate a preference for the CDM over the AQDM.

ACKNOWLEDGEMENTS

The authors are indebted to Herschel H. Slater, William M. Cox, Russell F. Lee, and others of the Air Quality Management Branch for the emission inventory and air quality data for the New York Region and the results of the computations by the AQDM. They are also indebted to Frank Gifford and Steve Hanna for their unpublished manuscript indicating their recent studies of simple modeling, and to Lea Prince and Dot Avent for their valuable assistance.

REFERENCES

Briggs, G. A., 1969: Plume Rise. AEC Critical Review Series. Oak Rdige, Tenn., USA, Atomic Energy Commission, Division of Technical Information, 81 p. (Available from NTIS as TID-25075)

Calder, Kenneth L., 1970: Some miscellaneous aspects of current urban pollution models. Proc. of Symposium on Multiple-Source Urban Diffusion Models, 13 p. US Envir. Prot. Agency Air Pollution Control Office Pub. No. AP-86.

Calder, Kenneth L., 1971: A climatological model for multiple source urban air pollution. Proc. 2nd Meeting of the Expert Panel on Air Pollution Modeling, NATO Committee on the Challenges of Modern Society, Paris, France, July 1971, 33 p.

Environmental Science Services Administration, 1969: Local climatological data, New York, N. Y., La Guardia Airport.

Gifford, F. A., Jr., and Hanna, Steven R., 1971: Urban air pollution modeling. Proc. 2nd International Clean Air Congress. Edited by H. M. Englund and W. T. Berry, Academic Press, New York and London, 1146-1151.

Gifford, F. A., Jr., and Hanna, S. R., 1972: Modeling urban air pollution. Atmos. Environ. in press.

Hanna, Steven R., 1971: A simple method of calculating dispersion from urban area sources. J. Air. Poll. Contr. Assoc., 21, 12, 774-777.

Holland, J. Z., 1953: A meteorological survey of the Oak Ridge area. 554-559, Atomic Energy Comm., Report ORO-99, Washington, D. C., 584 p.

Martin, Delance O., 1971: An urban diffusion model for estimating long term average values of air quality. J. Air Poll. Contr. Assoc., 21, 1, 16-19.

Martin, Delance O., and Tikvart, Joseph A., 1968: A general atmospheric diffusion model for estimating the effects of air quality of one or more sources. APCA Paper 68-148, Presented at 61st annual APCA meeting, St. Paul Minn., June 1968.

Pasquill, F., 1962: Atmospheric Diffusion. London, D. Van Norstrand, 297 p.

TRW Systems Group, 1969: Air quality display model. Prepared for Department of Health, Education, and Welfare, Public Health Service, Consumer Protection and Environmental Health Service, National Air Pollution Control Administration, Washington, D. C., Contract No. Ph-22-68-60. (Available from NTIS, Springfield, Va., 22151 as PB-189-194)

Turner, D. B., 1967: Workbook on atmospheric dispersion estimates. National Air Pollution Control Administration, Cincinnati, Ohio, PHS Pub. No. 999-AP-26, 84 p.

Zimmerman, John R., 1971: Some preliminary results of modeling from the air pollution study of Ankara, Turkey. Proc. 2nd Meeting of the Expert Panel on Air Pollution Modeling, NATO Committee on the Challenges of Modern Society, Paris, France, July 1971, 28 p.

Zimmerman, John R.,1972: The NATO/CCMS air pollution study of St. Louis, Missouri. To be presented at 3rd Meeting of the Expert Panel on Air Pollution Modeling, NATO Committee on the Challenges of Modern Society, Paris, France, October 1972.

Chapter IX

A REVIEW OF SOME TECHNIQUES FOR INVESTIGATING MESOSCALE TRANSPORT IN THE PLANETARY BOUNDARY LAYER

by

Larry L. Wendell

Air Resources Laboratories
Environmental Research Laboratories
NOAA, Idaho Falls, Idaho

1. Mesoscale transport estimates from a network of wind towers.

There has been a great deal of theoretical, numerical and observational work done on the vertical wind structure of the planetary boundary layer, but comparatively little on the mesoscale horizontal variation of the wind in this layer. At the present time the most common operational practice for estimating the transport and diffusion of a pollutant from a single source involves only the wind at the source. The critical question to be considered is how representative is the wind at the source in computing transport over distances of 50 to 100 km? In an attempt to determine the mesoscale horizontal variation of the wind in the lower portion of the planetary boundary layer, hourly averaged wind data from a randomly spaced collection of 21 wind stations within an area of 12,420 km^2 has been used to make a preliminary investigation of the problem (Wendell, 1972).

The scale of concern in this work is about an order of magnitude smaller than the synoptic scale. This is shown by an outline of the computational grid (rectangular box in southeastern Idaho) on a map of the western United States in Figure 1. The grid is approximately 86 km wide and 130 km long. The topography of the area is shown in Figure 2. The severe height variation is shown only qualitatively through a shadowed photograph of a relief map. The gentle height variation over the relatively flat plain is depicted by the height contours. The area in which the terrain is less than 5,000 ft is stippled to emphasize the large fishhook-shaped depression in the plain. The solid black dots show the locations of the towers with the wind sensors. The sensor heights were 15 m or above. All calculations were restricted to the area to the right of the dashed line.

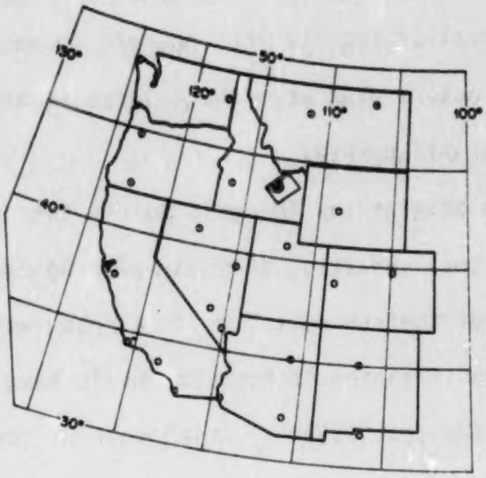


Figure 1. Location and extent of computational grid for mesoscale wind observations. The solid border of the rectangular box in southeastern Idaho contains all the observation locations, but no calculations are carried out for the area northwest of the dashed line. The solid black area represents the geographical extent of the National Reactor Testing Station (Wendell, 1972).

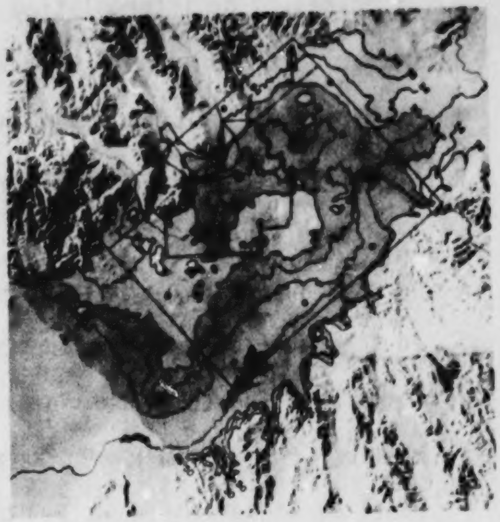


Figure 2. Relief map of the Upper Snake River Plain in southeastern Idaho. The values shown on the few contour lines over the plain are in hundreds of feet. The stippled area within and adjacent to the grid indicates the area of altitude less than 5,000 ft MSL. The tick marks along the border of the grid indicate the grid-point separation, 5.33 mi. The letters a, b, and c show the location of three prominent buttes. The solid dots indicate the location of the wind towers (Wendell, 1972).

The basic calculation was an interpolation of the wind components measured at the non-regularly spaced towers to a regularly spaced grid of points. The interpolation technique involved a weighted averaging of the velocity components from several of the stations nearest to each of the grid points. The weighting factors used were the inverse squares of the distances from stations to grid points.

When the wind components are obtained at the grid points they may be used in several types of analyses. However, they may also be used to enhance the appearance of a plot of the raw data for visual observation. Computer produced plots of the wind fields at 6 hour intervals have been made for the entire year of 1969 (Wendell, 1970). An example of these plots is shown in Figure 3. The winds measured at the tower locations are plotted in the standard format of shaft and barbs. The winds interpolated to the grid points are plotted as vectors, with their length directly proportional to the speed. In these plots the 5,000 ft contour is included with the outline of the U. S. Atomic Energy Commission's National Reactor Testing Station.

One of the most interesting features of the 1969 wind field plots was the strong conformity of the flow patterns to the fishhook-shaped depression. Varying degrees of this conformity were observed during some portion of about 60 percent of the days of the year. The two series of plots shown in Figure 3 are examples of this phenomenon. During about 12 percent of the days of 1969 the cyclonic bending of the flow in the upper portion of the grid developed into a distinctive circular shaped eddy which persisted for several hours.

It is quite obvious that flow patterns of the type just discussed would be very poorly represented by the wind at a single location. Flow

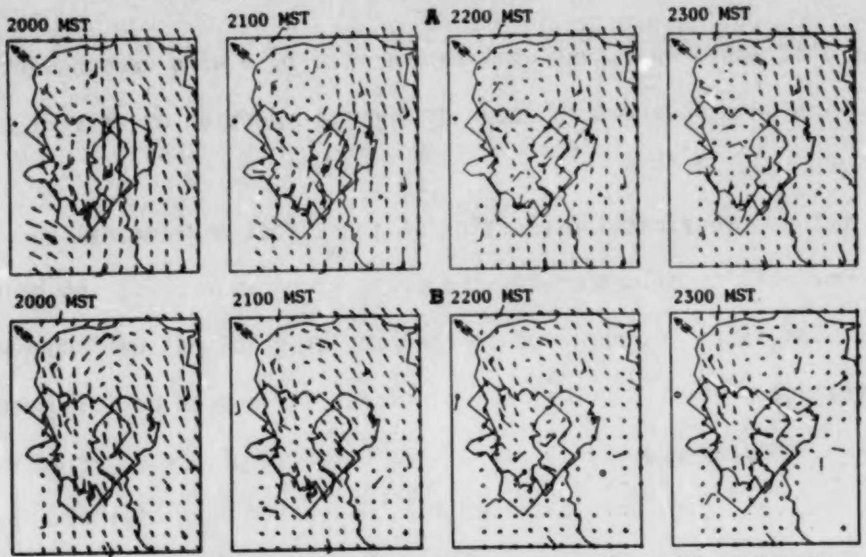

2000 MST
2100 MST
A 2200 MST
2300 MST
2000 MST
2100 MST
B 2200 MST
2300 MST

Figure 3. Examples of the flow pattern over the grid conforming to the topography. A 4-hr series is shown for two seasons of the year, (A) winter (Feb. 9, 1969), (B) spring (May 13, 1969). The 5,000-ft contour is included for reference purposes (fig. 2). The wind data from each station are plotted in standard form and the interpolated winds are plotted as vectors at each grid-point (Wendell, 1970).

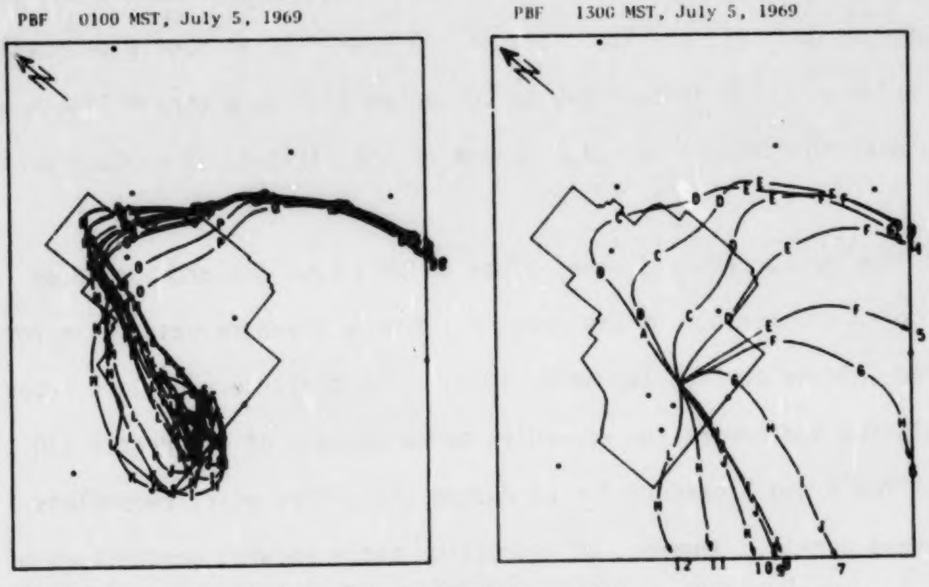

PBF 0100 MST, July 5, 1969
PBF 1300 MST, July 5, 1969
4
5
12
11
10
9
7

Figure 4. Trajectories of hypothetical particles released hourly and transported by a time series of objectively interpolated wind fields. The numbers at the ends of the trajectories indicate the order of release, and the letters along the trajectories represent hourly positions (Wendell, 1972).

patterns that would have been well represented by a wind measurement at one location were observed to occur during some portion of only 21 percent of the days of 1969.

To get a more direct observation of the effect of temporal and spatial variability of mesoscale wind patterns on transport, the hourly averaged wind data, interpolated to the regular grid, was used to construct trajectories of hypothetical particles introduced serially into the flow. Computer produced plots of trajectories of these particles, released once an hour, were obtained for the entire year of 1969. Examples of these plots are shown in Figure 4. These two series of trajectories indicate the path of 12 particles released one hour apart beginning at the times shown above each plot. The numbers at the ends of the trajectories indicate the order of release and the letters along the trajectories indicate the locations of the particles at hourly intervals after release. Like letters may be connected to form a streak line and may be used to estimate the time change of the position of a plume center line.

A long series of trajectory plots of this type can provide an estimate of a climatology of the transport from a given release point for selected release periods (Wendell, 1972). The trajectory pattern types are selected and are ranked according to percentage of occurrence (20 percent for A and 3 percent for L) during the entire year, regardless of release period. However, an associated table showing percentages of occurrence according to release period and season provides a fairly detailed picture of the variation of transport conditions for the given release location.

It may be noted from some of the trajectory pattern types that the spatial variability in the flow has played a large part in determining the pattern. To obtain a more direct comparison of the wind field and single station produced trajectories, several sets of trajectories were recomputed using only the source wind as if it applied over the whole grid. Some of these results are shown in Figure 5. The trajectories in the upper plots (WF) were obtained from the wind fields while those in the lower plots (SS) were obtained using the source wind only. The differences in the transport are quite apparent.

It should be pointed out that the transport, represented by wind measurements from these towers, is restricted to a layer in which these measurements are representative. During stable conditions most of the material released would remain in this layer and the tower winds should provide a reasonable estimate of the transport and generally a much better estimate than one from a single station.

2. Transport estimate from constant density balloons

It would be very valuable to have detailed information about the structure of the flow within the first 500 meters above the ground, but a network of towers extending to this height would not be feasible. Other possibilities for gaining the information would be a network of large tethered balloons or stations which frequently released and tracked pilot balloons to 500 m or higher. These techniques are feasible but somewhat costly. All of the methods considered to this point involve taking measurements at fixed stations to deduce the transport through the network of stations.

A method which measures the flow in a more direct sense is that of using a radar to track a constant density balloon. The difficulty in

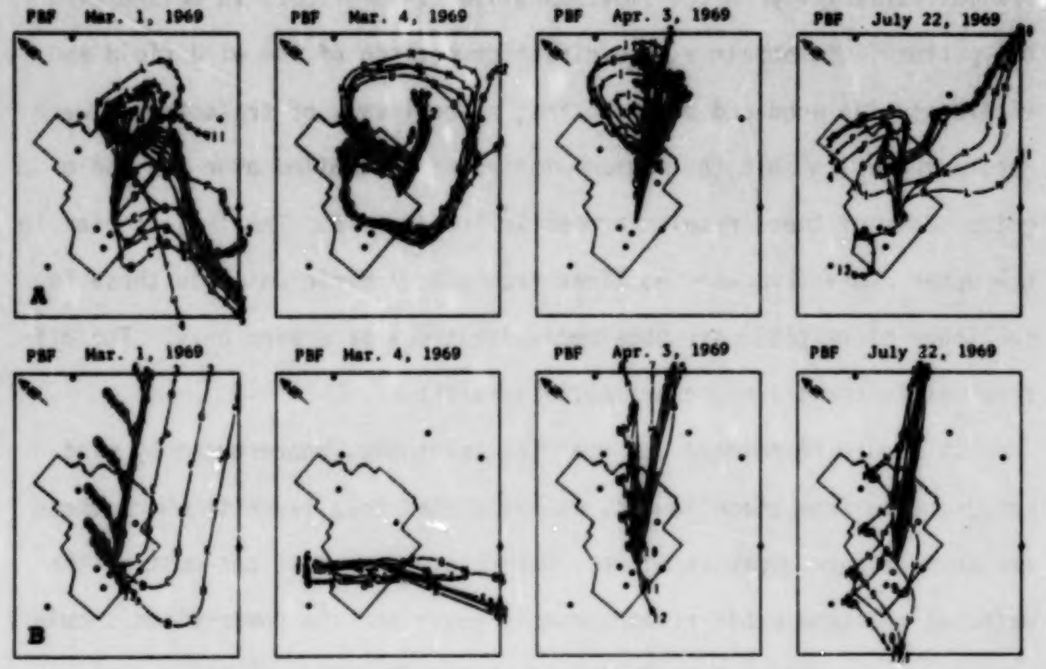


Figure 5. Comparison of (A) trajectories derived from the wind field with (B) trajectories derived from the source wind applied over the whole grid for the corresponding time periods (1300 MST on days indicated), (Wendell, 1972).

tracking a low-flying target through ground clutter was overcome through the development of an electronic device which, when triggered by the radar signal, responds by transmitting a signal of its own (Dickson & Pound, 1961). A fairly complete list of references is provided by Angel, et. al. (1972) to the work done in recent years in which the radar-tetroon-transponder system has been utilized to study various characteristics of air motion in the planetary boundary layer.

Tetroon trajectories have been compared with wind field derived trajectories (Van der Hoven 1971, Angell et. al. 1972) with widely varying results for individual comparisons. An example of these comparisons is shown in Figure 6. One would have to say, in summary of observations thus far, that if the tetroon flies low enough or there is little vertical wind shear the trajectories are generally quite similar. However, under the conditions of strong temperature inversions and local topographic anomalies, the trajectories can be very different. This does not mean that one type of trajectory is more correct than the other. It simply means that when the tetroon flight level is above the tower sensors, the difference in the trajectories is a reflection of the wind shear. This suggests that the two methods of investigating the mesoscale circulation of the planetary boundary layer could be used to complement each other.

In two recent field experiments carried out in Oklahoma and Colorado by Air Resources Laboratories personnel, both types of data were gathered. The data is still undergoing analysis, but preliminary results indicate that cases of extremely large direction shear are not uncommon under temperature inversion conditions.

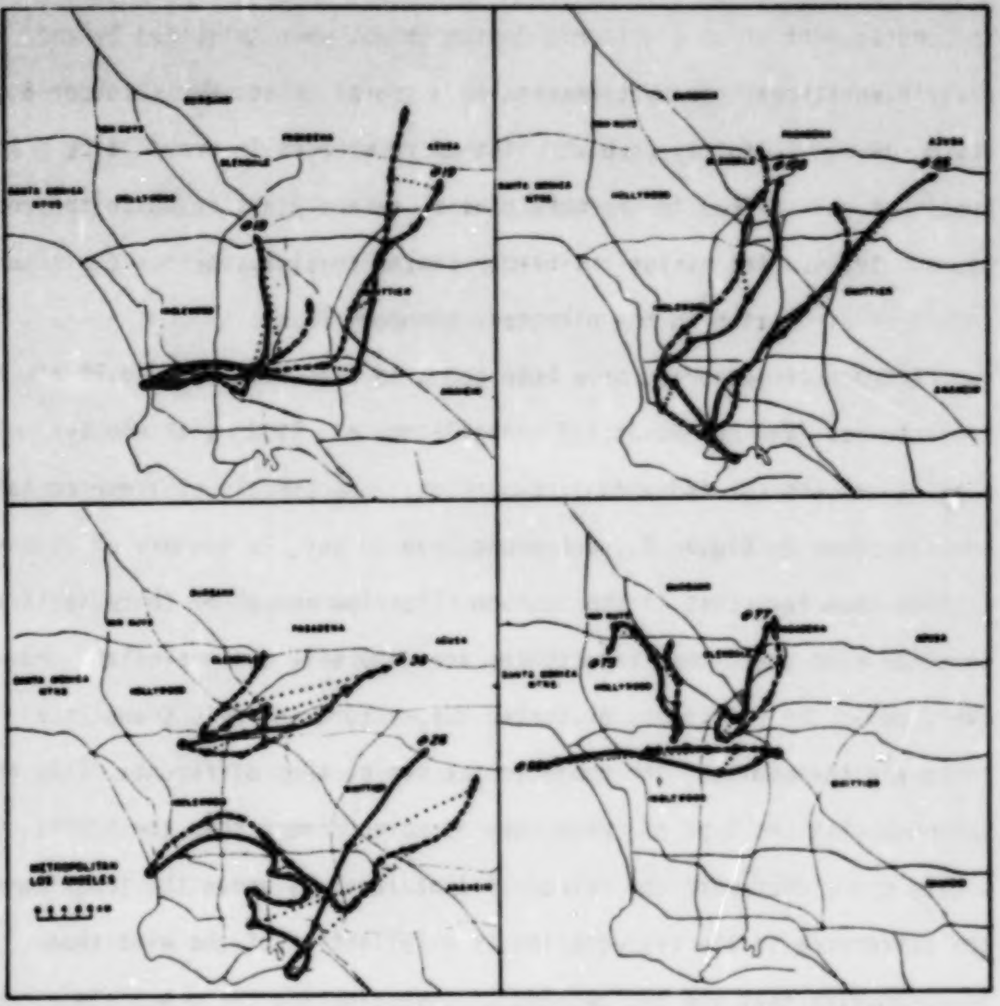


Figure 6. Comparisons between tetroon (solid line) and derived surface (dashed lines) trajectories for some of the tetroon flights discussed previously. The surface air trajectories were originated at the time and place of the tetroon trajectories. The dots along the trajectories are at 1-hr intervals, while the dotted lines are isochrones connecting tetroon and surface trajectory positions for the same time. The tetroon flight numbers are given at the ends of the solid trajectories (Angell, 1971).

3. Comparisons of wind field and tetroon trajectories with a plume centerline.

In an attempt to determine how well trajectories of the two types discussed above may represent the transport of a real tracer, data from a diffusion experiment with methyl iodide gas have been compared (Start et. al. 1972). The gas was released from a 76 meter stack over a one hour period. Samples were collected at 1 m above the ground on four successive arcs out to 76 km. Tetroons were launched at about 20 minute intervals during the methyl iodide release. Wind data from the mesoscale tower network was used to construct trajectories with release times corresponding to those of the tetroons.

The composite plot of the tetroon trajectories shown in Figure 7 indicates good agreement between the measured peak concentrations and the envelope of tetroon trajectories out to 60 to 65 km. Beyond the 19 km arc the envelope of wind field derived trajectories, Figure 8, is shifted to the left of the peak concentration line. This would indicate that the tracer, under the mildly unstable conditions existing during the experiment, gradually rose to the level influencing the tetroon trajectories (generally below 600 m, occasionally to 1600 m.) The directional shear through this layer averaged near 5^0 in this experiment and the tracer path was fairly well bracketed by both sets of trajectories. In cases of greater directional shear the path of the tracer would depend on the vertical extent or location of the plume. However, with a knowledge of the thermal stability and data provided by tetroons and a network of wind towers, one would have some fairly powerful tools with which to estimate the transport of the tracer.

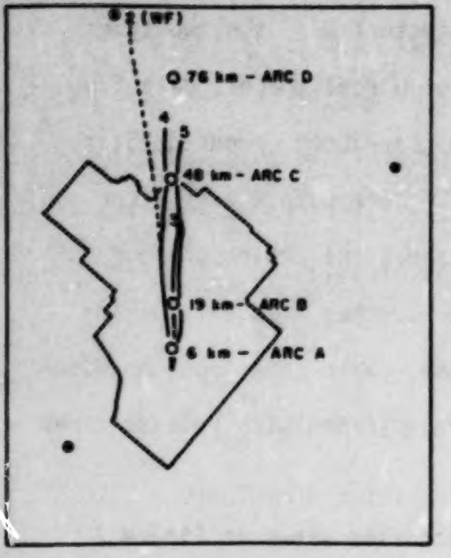

2 (WF)
76 km - ARC D
4
5
48 km - ARC C
3
19 km - ARC B
6 km - ARC A

Figure 7. Composite plot of tetroon trajectories #3, 4, and 5. Dashed line locates wind field derived trajectory beginning at 1430 MST. Locations of peak measured methyl iodide concentrations are denoted by open circles (Start, 1971).

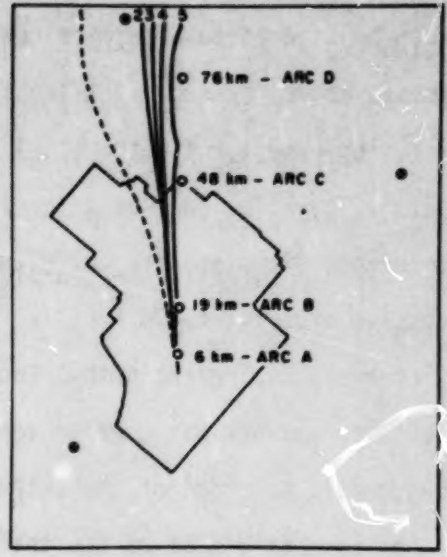

1
2
3
4
5
76km - ARC D
48 km - ARC C
19 km - ARC B
6 km - ARC A

Figure 8. Composite plot of wind field derived trajectories. Dashed line locates trajectory for 1 hour before the methyl iodide release. Locations of peak measured methyl iodide concentrations are denoted by open circles (Start, 1971).

All the work described in this review is concerned with the transport of a tracer rather than the dispersion. Atmospheric diffusion modeling and experimentation have been performed very extensively by many investigators. The very complex problem of mesoscale circulation and its effect on the transport of airborn material has received comparatively little attention. Observational programs like those described above, are demonstrating the complexity of the circulation which can exist in this layer.

References:

Angell, James K., Pack, Donald H., Dickson, C. Ray and Hoecker, Walter H., "Urban Influence on Nighttime Airflow Estimated from Tetroon Flights," Journal of Applied Meteorology, Vol. 10, No. 2, April 1971, pp 194-204.

Dickson, C. Ray, and Pound, Earl F., "A Radar Transponder for Determining Meteorological Trajectories," Proceedings of the 9th Weather Conference, Kansas City, Mo., Oct. 1961 pp 379-383.

Start, George E., Dickson, C. Ray, and Voilleque, Paul G., "Comparisons Among Tracer, Tetroon and Wind Field Derived Trajectories and Some Diffusion Estimates", Las Cruces, New Mexico, Dec. 7-10, 1971, Sandia Laboratories, March 1972, pp 280-285.

Van der Hoven, Isaac (Editor), "Atmospheric Transport and Diffusion in the Planetary Boundary Layer", NOAA Technical Memorandum, ERL ARL 28, U. S. Department of Commerce, Air Resources Laboratories, Silver Spring, Md., Jan. 1971.

Wendell, Larry L., "Mesoscale Wind Fields and Transport Estimates Determined from a Network of Wind Towers", Monthly Weather Review, Vol. 100, No. 7, July 1972, pp 565-578.

Chapter X

MATHEMATICAL MODELING OF AIR QUALITY THROUGH CALCULATION OF ATMOSPHERIC TRANSPORT AND DIFFUSION

[A new chapter in a revised U.S. air quality criteria document for sulfur oxides]

by

Kenneth L. Calder*

ENVIRONMENTAL PROTECTION AGENCY
NATIONAL ENVIRONMENTAL RESEARCH CENTER
DIVISION OF METEOROLOGY
Research Triangle Park, North Carolina

3rd Meeting of Panel on Modeling of NATO Committee
on the Challenges of Modern Society

Paris, France
October 2-4, 1972

---

*On assignment from National Oceanic and Atmospheric Administration, Department of Commerce.

MATHEMATICAL MODELING OF AIR QUALITY THROUGH CALCULATION OF ATMOSPHERIC TRANSPORT AND DIFFUSION

A. INTRODUCTION

A mathematical model of air quality aims to provide a quantitative causal link between the intensity and spatial distribution of the sources of air pollution and the measured atmospheric distribution of air quality. It is thus an essential basis for any rational control of air pollution and particularly important when considerations of cost-effectiveness relative to alternative control strategies are of concern.

Since the fundamental physical processes that must be represented in a model are those of the transport and diffusion of pollutant by the turbulent air flow, it may be anticipated that there will be many aspects of the modeling that are relatively independent of the nature of the pollutant considered. This will certainly be the case when the pollutant is gaseous or composed of fine particulate matter (so that questions of gravitational settling are not relevant), and when the concentration is not so high as to influence appreciably the density of the air, and when the pollutant can be treated as inert and not subject to chemical and physical transformation, and when removal from the atmosphere by various natural processes, such as precipitation, can be disregarded. In this chapter primary concern is with modeling air pollution concentrations due to gaseous sulfur dioxide. However, from what has been said, many of the physical considerations will be common to the atmospheric dispersion of other relatively stable gaseous pollutants or to very fine particulate matter.

Although the subject of air quality modeling (1,2,3)* for urban or regional pollution is only a little more than one decade old, because of its vital importance for so many problems of scientific air management, it has recently been receiving very concentrated attention and vigorous development. This has resulted in a plethora of technical papers and publications and many modeling considerations are actually still in the process of undergoing critical evaluation and intercomparisons. Thus the references to the present chapter contain over forty that have only appeared in the 1970's and this intentionally excludes all that are concerned primarily with the modeling of reactive pollutants. Many of these references (2,4,5,6,7,8,9,10) provide important definitive discussions and are of very recent origin or even still in press. Under these circumstances, and because of the very rapid stage of development of the subject, it has not seemed appropriate to attempt still another general account. Instead the present chapter indicates briefly, and in a qualitative fashion, some of the more important questions for modeling of SO_2 concentrations and then cites appropriate recent technical references where the subject is discussed more fully. In any case, due to the obvious complexity of atmospheric and terrain situations in the real world, the subject of meteorological dispersion modeling is one that is most effectively handled by specialists. The latter will probably be quite familiar with the extensive literature of the subject and the limitations of the various approaches that have been proposed.

---

*The references of this chapter are intended only to provide a guide to the modeling techniques that are currently under development and reported in the literature. Although the list is long, it is be no means exhaustive, and failure to include a publication is, of course, no reflection on its merit.

Finally, it should certainly not be concluded from the numerous references that there is a corresponding wide variety of modeling approaches available. In fact the majority of current mathematical models for both large point-source releases of SO_2 (as for power plants burning fossil fuel) and also the multiple-source situations that characterize urban areas, all stem from the classical so-called Gaussian plume representation of the concentration distribution from a single elevated point-source release (2,11, 12,13,14,15). In many cases the differences are primarily matters of detail that are not fundamental but rather matters of individual preference. It may be anticipated that with the intensive study that the topic is receiving, some consolidation of the better features of the validated operational models that have been reported will shortly be available. This is one of the objectives of the forthcoming major field program (Regional Air Pollution Study) that is planned by the U. S. Environmental Protection Agency for St. Louis, Missouri, for the years 1972-77 (16).

B. METHODS FOR ESTIMATING ATMOSPHERIC DISPERSION

The dispersion of airborne material by the natural wind is typified by the travel and spreading of the smoke plume from a factory chimney and is clearly a very complex phenomenon. This complexity is largely a result of the fact that the atmospheric flow is generally turbulent and associated with eddies having a wide spectrum of sizes. Even under the most idealized conditions, such as are encountered in the laboratory, the dynamics of turbulence and the turbulent diffusion of a passive pollutant are generally regarded as the most intractable problems in the whole of fluid dynamics at the present time. These problems are even more complicated in the atmosphere because of the very pronounced effect of the vertical temperature structure in either increasing or decreasing the diffusive power of the atmosphere. In addition, of course, severe complications also arise from the frequently non-uniform and irregular nature of the earth's surface. It is therefore not surprising that no general complete theory has been formulated to express the physical relationship between ambient concentrations of air pollutants and the causative meteorological factors and processes. At the same time a large body of empirical data on atmospheric dispersion has been accumulated over the past several decades from activities connected with Chemical-Biological-Radiological warfare, atomic energy, and air pollution research. Partial or semi-theoretical expressions and working equations, including appropriate values of the diffusion parameters derived from these ad hoc field studies for limited classes of situations, have proved useful in the solution of a variety of air pollution problems, particularly where the diffusing material is chemically inert or almost nonreactive.

The technical literature discussing meteorological factors affecting dispersion of windborne material is very extensive and continuously augmented by articles that regularly appear in the meteorological journals. A few recent authoritativediscussions of this broad subject are provided in the references (4,9,13,14,15). These discuss the effects of such factors as wind direction, wind speed, atmospheric stability and turbulence, and depth of the mixing layer (i.e., the layer in which the turbulent dispersion of pollutant occurs). Some very useful practical guides to the prediction of dispersion of a relatively stable pollutant like SO_2, may be specially noted (6,11,13,14,17). These emphasize the preeminent position at the present time of the Gaussian plume formulation for the spatial distribution (particularly at ground level) of the pollutant concentration from an elevated point-source, and indicate how the numerical values of the parameters in this formulation can be estimated in terms of the prevailing meteorological conditions and the height of the source above ground. Since most of the elevated pollutant releases are associated with hot gas release from a stack, the "effective" height normally exceeds the physical height of the stack by an amount determined by the buoyant rise of the plume. This special topic is itself the subject of extensive literature and a large number of semi-empirical plume rise equations have been developed over the years(12,18,19,20,21).

The various recommended dispersion prediction schemes that are currently available refer mainly to rather idealized conditions of flow and terrain from which there may frequently be large deviations in practical situations. It is important in these cases to keep in mind that any meaningful use or adaptation of the prediction formulae will require professional meteorological advice. Again a caution may be appropriate, in the present state of knowledge, against overselling the capabilities of mathematical models and meteorological knowledge, as this may sometimes be a temptation, in view of the ready availability and ease of comprehensive electronic computer-produced output.

In utilizing any dispersion estimates it is important to recognize the fundamental probabilistic nature of atmospheric behavior. There are random variations in the airflow and in the apparent dispersive power of the atmosphere. This arises because the flow is turbulent and involves a wide spectrum of eddy sizes. This strictly implies that over a spectrum of scales of interest the dispersion estimates can at best only provide information on statistical quantities, such as time-averaged concentrations, from which behavior on individual occasions may depart to a considerable degree. Recognition that the apparent concentration distribution is highly dependent on the specific averaging time that is used is quite fundamental and has been the subject of several special studies (13,22,23,24).

In spite of the above qualifications, it is generally agreed that current modeling procedures for practical estimation of dispersion frequently provide extremely useful results that would be very difficult or expensive to obtain by any other means. In unusually complex situations, however, it may be desirable to check the initial estimates obtained by use of a model through special tracer releases. Major improvements in the present somewhat empirical approach will require a much improved understanding of the turbulent exchange processes occurring in the complex boundary layer situations often encountered in real pollution problems. Intensive meteorological studies of the wind, turbulence, and temperature structure of the urban boundary layer will help provide this understanding, and such studies are planned for the forthcoming EPA Regional Air Pollution Study previously mentioned.

C. EFFECTS OF SINGLE POINT SOURCES

Stacks several hundreds of feet high provide a recognized method for keeping the concentrations at ground level within acceptable limits under most circumstances, even when the pollutant releases are quite massive, as in the case of power stations and many industrial plants. The vital importance of the tall stack as a means for reducing the concentration level close to the source, where the reduction is most needed, have occasioned a large number of special studies as indicated by a 1969 bibliography (21) that lists over two hundred references to various atmospheric phenomena and related aspects of tall stacks. Because most of the earlier studies of stack releases only involved heights of generally less than 300 feet, dispersion data directly applicable to tall stacks, such as those of large electric power stations, are of recent origin. Among the first were those obtained by the Tenessee Valley Authority (25) in a full scale study of SO_2 dispersion from several 300-foot stacks. Also notable are the studies of the Central Electricity Research Laboratories in the United Kingdom (12). More recently a comprehensive field study (Large Power Plant Effluent Study (LAPPES)) was completed by the Environmental Protection Agency (26, 27,28) to evaluate the extent and effects of SO_2 pollution resulting from the largest complex of coal-burning generating stations in the United States. This Western Pennsylvania complex has stacks at least 800 feet high. These experiments extended over several years and consisted of ground-based and airborne plume measurements supported by extensive meteorological observations, and with very complete information on plant operational parameters to characterize the SO_2 emissions. This data has yet to be exhaustively analyzed although it should lead to a much improved modeling capability for SO_2 dispersion from tall stacks. Some preliminary results (29) and a report on a field investigation (30) at the same location of SO_2 washout by natrual precipitation from the plume of one power plant have been published. Because, at the present time, most estimates of dispersion from tall stacks are perforce based on somewhat speculative extrapolations of what is known of lower level emissions, these estimates should, whenever possible, be checked against some measured SO_2 concentration values.

The dispersion behavior of a stack plume (2, 13, 14) is normally classified on the basis of the ambient conditions of atmospheric stability, and the plume is described as looping (plume rapidly spread in upward and downward loops produced by thermally induced eddies), coning (a simple plume, shaped like a cone, with a horizontal axis), fanning (plume with very little spread in vertical direction but a meandering trajectory in the horizontal plane), lofting (plume spread limited in downward direction but spreading in upward direction), or inversion breakup fumigation (rapid downward spread of plume in a stable surface layer as the stability is destroyed by mixing following sunrise). Theoretical calculations of pollutant concentrations at ground level are normally only made for the looping, coning and fumigation situations (2, 6, 11, 13, 14, 17, 31, 32) although in many cases these are no more than elementary adaptations of the fundamental Gaussian plume formulation subject to the constraints imposed by conservation of matter. Furthermore the above classification of plume behavior is strictly most characteristic of conditions in the lowest 1000 feet of the atmosphere. However, effluents from tall stacks are often located in the range 1000-3000 feet above ground because of the large plume rise due to buoyancy and inertial effects so that the classifications are frequently not applicable or appropriate. Evidently, in the present state of knowledge, prediction of the behavior of plumes from tall stacks places a maximum demand on meteorological knowledge and stretches this beyond its present limits.

Mention has been made of plume rise and its effect in increasing the effective height of release of pollutant. This becomes a very important part of the modeling of dispersion from tall stacks because of its large magnitude, and has been the subject of several analyses (12, 13, 18, 19, 20). The behavior of plumes at large power plants under inversion breakup considerations has also been the subject of a full-scale study (31).

Because of the irregular and random nature of plume behavior under many conditions, successful modeling will eventually need to explicitly recognize the probabilistic nature of the problem. Some initial attempts (33, 34) to provide a statistical approach to air quality in the neighborhood of a single point source under somewhat idealized conditions may point the way. Since critical biological effects can occur from short-period exposures, as when some plants are exposed to SO_2, some ability to model the statistics and the frequency distribution for short period (say,1 hour) exposures is particularly important.

Again since the tall stacks of modern power plants are often located in irregular terrain, models are needed that include consideration of topographical effects. As a particular example, it has been recognized for some time that impingement of plumes on hillsides or mountains may result in high concentrations even at great distances from the source location. A notable recent attempt to incorporate such terrain considerations is the Report of the Meteorology Working Group of the Southwest Energy Study (8). The Helena Valley of Montana has also been the subject of some recent SO_2 dispersion modeling efforts (35), including short-term and long-term estimates, while large point source modeling considerations have also been applied to provide estimates of SO_2 concentrations from the Four Corners Power Plant, New Mexico (36).

D. MULTIPLE-SOURCE URBAN DIFFUSION MODELS

Extensive recent literature (3,5,6,7,9,10,37,38,39,40,41,42,43,44, 45,46,47,48,) relating to the mathematical modeling of the pollutant distribution resulting from the multiple sources comprising an urban area indicates the intense and growing current interest in the subject. This arises as mathematical modeling provides the unique rational basis for quantitative comparisons between various pollution control strategies. For the massive single point-source release, which often dominates the entire pollution situation in its neighborhood, the principle of proportional reduction as between pollution concentrations everywhere in the source neighborhood and the emission rate, can provide a sufficient basis for achieving a prescribed level of air quality, and be actually applied in terms of observations of pollutant concentration in the atmosphere. This is no longer true, however, for the multiple-source urban situation, and a uniform reduction of all sources by the same factor irrespective of their nature, as a means of achieving a proportional reduction in pollution concentration, would be a most uneconomic control strategy. Clearly what is required is a means of estimating the relative contributions of different sources in an area to the total concentration at any receptor location, and this is precisely the kind of information that is available from the multiple-source model.

Most practical multiple-source models are based on the simple

Gaussian plume formulation as used for the single point of release. They require, as a preliminary to estimation of atmospheric dispersion, that the relevant meteorological conditions (such as wind direction, wind speed, atmospheric stability, etc.) be specified. A different approach which, however, still requires input of the meteorological conditions is the so-called gradient transfer theory, which assumes that the transfer of material by eddies in the atmosphere can be represented in a form analogous to molecular diffusion, although this has not yet reached the stage of operational use (41,44). A very sophisticated approach (49) also under study simultaneously predicts the meso-scale meteorological conditions together with the diffusion of pollutant. If successful this will obviate the necessity for treating the meteorological conditions as an independent input to the urban dispersion model. The model has the general nature of a meso-scale numerical weather prediction model. In most simple Gaussian plume models, the meteorological conditions that specify the dispersion from a single source are assumed to be uniform over the whole urban area, although regional pollution models that recognize a spatial variation have been proposed (50).

Although, for a "stable" pollutant like SO_2, the multiple-source model is simply an integration derived by superposition of the effects produced by the many individual sources, this does in practice lead to considerable complexity that normally necessitates use of a computer. Because of the averaging effects arising from the superposition of many individual plumes some of the fine details of the latter will become relatively unimportant in the multiple-source prediction problem which may thus be less difficult than that for the large isolated single source.

The distributed release of SO_2 from an urban area is specified through an emissions inventory that treats the emissions as either large individually specified point sources or as small sources that are averaged over an area and treated as a continuous surface distribution. Inaccuracies in the emissions inventory will, of course, be directly reflected in the model concentration predictions, and are a frequent major limitation on the accuracy of the predictions. Also important is the fact that, although the total SO_2 emissions for a long time-period, like a season or year, can often be estimated with some accuracy, it is frequently necessary for the modeling procedures to make estimates for short-time-periods, say on an hourly basis, and this is a much more difficult problem involving a high degree of empiricism (46).

In utilizing the Gaussian plume formulation for a single source, it is assumed that over a short time-period such as one hour, the meteorological conditions can be regarded as steady-state with a unique specification that can be used as input to the concentration formula. More general and variable meteorological conditions are then treated as though they are piecewise steady-state in time. By computing the concentration at any receptor location for each of a number of short-time-periods for which the meteorological conditions are known, it is possible to obtain the frequency distribution of the concentration values (46, 51) or other statistical quantities that may be of interest, such as the long-term or overall average value. Although the frequency distribution approach appears preferable, and provides more information, in some models the long-term average concentration values are obtained directly by a summation and without the sorting process required to determine a frequency distribution (39, 43). Under conditions of light winds and calms such as are frequently encountered under episodic conditions for the build-up of SO_2 pollution, the Gaussian plume modeling approach is not readily applied although a possible algorithm for this special situation has been tentatively proposed (47).

In modeling SO_2 dispersion, the possibility of chemical transformation processes always needs to be considered and is the subject of several recent papers (52, 53, 54). These processes appear to be very complex in an urban atmosphere which is normally a mixture of many pollutants, and estimates of the half-life of SO_2 range from roughly one-half hour to several days. Since even one-half hour corresponds to an appreciable travel distance at normal wind speeds it may be expected that, except possibly in light wind conditions, the decay factor will not be an important one for multiple-source urban modeling, a situation that is probably reinforced by the fact that for area sources the prime contribution to the concentration at any receptor location normally comes from sources in its close neighborhood. The relatively minor effects of decay are also substantiated by the reasonable agreement between predictions and observations of air quality when this factor is disregarded. However, it could become an important consideration under the conditions of very light winds occurring with so-called stagnation conditions.

Although, as previously indicated, some aspects of the concentration frequency distribution may be derived from theoretical modeling, empirically established statistical data on air quality are very valuable. Thus examination of extensive urban data shows that the concentration frequency distribution is often closely lognormal, for all averaging times, and this fact has been much used (22) as an empirical basis for discussing the effects of various averaging times. Some other selected references bearing on this topic are given at the end of this chapter (55, 56).

Despite the conceptual simplicity of most existing urban dispersion models the complicated details arising from the distribution of emissions and a wide variety of possible meteorological conditions most frequently necessitates that the calculations be made on a high-speed computer. This frequently obscures the more fundamental properties of the model in the massive details of particular applications, and it becomes a matter of considerable importance to systematically study the sensitivity of the concentration predictions to variations in inputs to the model. In some cases large variations in input may have little effect on the output, and it is then sufficient to specify the input in quite a crude fashion. Sensitivity analysis thus becomes important in simplifying the structure of the model (46). Rather convincing evidence is developing (6, 7, 38, 57) that quite major simplifications may be possible in multiple-source urban models for stable pollutants, and that the massive numerical effort involved in some recent developments may be drastically reduced without seriously affecting the accuracy of the predictions. This may be expected to be extremely valuable in the repetitive type of calculations that are often required for detailed comparisons between the effects on air quality of many different emission control strategies.

E. SUMMARY

This chapter discusses, in general qualitative terms, some of the more important aspects of the mathematical modeling of air quality, and with some emphasis on the prediction of SO_2 concentrations. The modeling considered refers to the calculation of atmospheric transport and dispersion once the intensity and distribution of pollutant emissions has been specified. It thus provides the rational basis for analysis of air quality in terms of the releases of pollutant. Since the subject has a very extensive recent literature and is still undergoing rapid development, prime concern has been to provide references to some of the more important studies, and especially since the many complexities of real situations will often require resolution by atmospheric dispersion specialists. The chapter considers some general problems involved in estimating the atmospheric transport and diffusion of pollutant and then discusses some of the special questions associated with large individual elevated point-sources, such as tall stacks. The problems of multiple-source urban diffusion modeling are also considered.

F. REFERENCES

1 Wanta, R. C. Meteorology and Air Pollution. In: Air Pollution, A. C. Stern (ed.), 2nd Ed., Vol. 1, New York, Academic Press, 1968, p. 187-226.

2 Somers, E. V. Dispersion of Pollutants Emitted into the Atmosphere. In: Air Pollution Control, Part One, Werner Strauss (ed), New York, Wiley-Interscience, 1971, p. 1-33.

3 Moses, H. Mathematical Urban Air Pollution Models. Argonne National Laboratory Report ANL/ES-RPY-001, April 1969, 69 p.

4 Pasquill, F. & F. B. Smith. The Physical and Meteorological Basis for the Estimation of the Dispersion of Windborne Material. In: Proceedings of the Second International Clean Air Congress, New York, Academic Press, 1971, p. 1067-1072.

5 Stern, A. C. (ed.) Proceedings of Symposium on Multiple - Source Urban Diffusion Models. U. S. Env. Prot. Agency, APCO Publ. AP-86 U. S. Govt. Printing Office, 1970.

6 Gifford, F. A. et al. Engineering Guide for Evaluating Dispersion of Sulphur Dioxide Emissions. State of Tennessee, Division of Air Pollution Control, Nashville, Tennessee, 1971.

7 Gifford, F. A. Transport and Dispersion in Urban Environments. Nuclear Safety, U. S. Atomic Energy Commission, Vol. 13-5, Sept. - Oct. 1972.

8 Van der Hoven, I. et al. Southwest Energy Study, Report of the Meteorology Work Group. U. S. Dept of Interior, Draft Report, March 1972, 113 p.

9 Pasquill, F. Atmospheric Dispersion of Pollution, Quart. J. Roy. Meteor. Soc., Vol. 97, 1971, p. 369-395.

10 Pasquill, F. Factors Determining Pollution from Local Sources in Industrial and Urban Areas. Meteor. Mag., U. K. Met. O, Vol. 101, 1972, p. 1-8.

11 Turner, D. B. Workbook of Atmospheric Dispersion Estimates. E.P.A., Office of Air Programs Publication AP-26, Revised 1970.

12 Roy. Soc. of London. A Discussion on Recent Research in Air Pollution. Phil. Trans. R. Soc. London, Vol. 265, 1969, p. 139-318.

13 Slade, D. H. (ed.) Meteorology and Atomic Energy 1968, U. S. Atomic Energy Comm., 1968, 445 p.

14 Smith, M. E. (ed.) Recommended Guide for the Prediction of the Dispersion of Airborne Effluents. Am. Soc. Mech. Eng., New York, 1968, 85 p.

15 Pasquill, F. Atmospheric Diffusion. New York, Van Nostrand Co., 1962, 297 p.

16 Collis, R. T. H. Regional Air Pollution Study: A Prospectus, Part I-Summary. Stanford Research Institute under EPA Contract 68-02-0207, Jan 1972, 88 p.

17 Carpenter, S. B. et al. Principal Plume Dispersion Models: T. V. A. Power Plants. J.A.P.C.A., Vol. 21, Aug. 1971, p. 491-495.

18 Thomas, F. W. et al. Plume Rise Estimates for Electric Generating Stations. J.A.P.C.A. Vol 20, March 1970, p. 170-177.

19 Tennessee Valley Authority. Full-Scale Study of Plume Rise at Large Electric Generating Stations. Muscle Shoals, Alabama, Sept. 1968.

20 Briggs, G. A. Plume Rise. U. S. Atomic Energy Commission, 1969, 81 p.

21 U. S. Dept of H.E.W. Tall Stacks, Various Atmospheric Phenomena and Related Aspects. Public Health Service, Consumer Protection and Environmental Health Service APTD 69-12, 1969, 99 p.

22 Larsen, R. I. L. A Mathematical Model for Relating Air Quality Measurements to Air Quality Standards. E.P.A., Office of Air Programs, Nov. 1971, 56 p.

23 McGuire, T. & K. E. Noll. Relationship between Concentrations of Atmospheric Pollutants and Averaging Time. Atmos. Env., Vol. 5 May 1971, p. 291-298.

24 Saltzman, B. E. Significance of Sampling Time in Air Monitoring. J. Air Pollution Cont. Assoc., Vol. 20, 1970, p. 660-665.

25 Gartrell, F. E. et al. Full-Scale Study of Dispersion of Stack Gases - A Summary Report. T.V.A. & P.H.S., Chattanooga, Tenn., Aug. 1964, 93 p.

26 Schiermeier, F. A. & L. E. Niemeyer. Large Power Plant Effluent Study (LAPPES), Vol. 1 - Instrumentation, Procedures, and Data Tabulation (1968). U. S. Dept of H.E.W. Nat. Air Poll. Control. Admin. Publ. No. APTD 70-2, June 1970, 410 p.

27 Schiermeier, F. A. & L. E. Niemeyer, Large Power Plant Effluent Study (LAPPES), Vol. 2 - Instrumentation, Procedures, and Data Tabulations (1967 and 1969). U. S. Dept. of H.E.W., Nat. Air Poll. Control Admin. Publ. No APTD - 0589, Nov. 1970, 337 p.

28 Schiermeier, F. A. Large Power Plant Effluent Study (LAPPES) Vol. 3 - Instrumentation, Procedures, and Data Tabulations (1970). U. S. Env. Prot. Agency, Office of Air Programs Publ, No APTD - 0735, Jan. 1972, 296 p.

29 Pooler, F. & L. E. Niemeyer. Dispersion from Tall Stacks: An Evaluation. In: Proceedings of the Second International Clean Air Congress, New York, Academic Press., 1971, p. 1049-1056.

30 Hales, J. M. et al. Field Investigation of Sulfur Dioxide Washout from the Plume of a Large Coal-Fired Power Plant by Natural Precipitation. Final Report, Batelle Memorial Institute Pacific Northwest Lab, Richland, Washington, Contract CPA-22-69-150, Mar. 1971, 214 p.

31 Tennessee Valley Authority. Report on Full-Scale Study of Inversion Breakup at Large Power Plants, Muscle Shoals, Alabama, Mar. 1970.

32 Pooler, F. Potential Dispersion of Plumes from Large Power Plants. U. S. Dept. of H.E.W., Public Health Service Publication No. 999-AP-16, 1965, 13 p.

33 Högström, U. A Statistical Approach to the Air Pollution Problem of Chimney Emission. Atmos. Env., Vol. 2, 1968, p. 251-271

34 Högström, U. A Method for Predicting Odour Frequencies from a Point Source. Atmos. Env., Vol. 6, Feb. 1972, p. 103-121.

35 U. S. Env. Prot. Agency. Helena Valley, Montana, Area Environmental Pollution Study. EPA Publication No. AP-91, 1972, 179 p.

36 U. S. Dept of H.E.W. Estimates of Air Pollution Concentrations from Four Corners Power Plant New Mexico. Public Health Service, Consumer Protection and Environmental Health Service, 1970, 1970, 122 p.

37 Englund, H. M. & W. T. Beery (ed.) Proceedings of the Second International Clean Air Congress. New York, Academic Press, 1971, 1354 p.

38 Gifford, F. A. & S. R. Hanna. Urban Air Pollution Modeling. In: Proceedings of the Second International Clean Air Congress, New York, Academic Press, 1971 p. 1146-1151.

39 Martin, D. O. An Urban Diffusion Model for Estimating Long Term Average Values of Air Quality. J.A.P.C.A., Vol. 21, Jan. 1971, p. 16-19.

40 Milford, S. N. et al. Developing a Practical Dispersion Model for an Air Quality Region. J.A.P.C.A., Vol. 21, Sept. 1971, p. 549-554.

41 Randerson, D. A Numerical Experiment in Simulating the Transport of Sulfur Dioxide through the Atmosphere. Atmos. Env., Vol. 4, Nov. 1970, p. 615-632.

42 Marsh, K. J. and V. R. Withers. An Experimental Study of the Emissions from Chimneys in Reading-III: The Investigation of Dispersion Calculations. Atmos. Env., Vol. 3, 1969, p. 281-302.

43 Calder, K. L. A Climatological Model for Multiple Source Urban Air Pollution. In: Proceedings of the Second Meeting of the Expert Panel on Air Pollution Modeling, NATO Committee on the Challenges of Modern Society, Paris, July 1971.

44 Lamb, R. G. & M. Neiberger. An Interim Version of a Generalized Urban Air Pollution Model. Atmos. Env., Vol. 5, 1971, p. 239-264.

45 Shieh, L. J. et al. Air Quality Diffusion Model, Application to New York City. I.B.M. J. RES. DEVEL., March 1972, p. 162-170.

46 Koch, R. C. & S. D. Thayer. Validation and Sensitivity Analysis of the Gaussian Plume Multiple-Source Urban Diffusion Model. GEOMET Report No. EF-60 prepared under EPA Contract CPA 70.94, Nov. 1971, 181 p.

47 Rote, D. M. et al. Studies of the Argonne Integrated - Puff Model, Argonne National Lab. Report ANL/ES-9, Oct., 1971, 106 p.

48 Croke, E. J. & J. J. Roberts. Chicago Air Pollution Systems Analysis Program Final Report. Argonne National Laboratory Report ANL/ES-CC-009, Feb. 1971, 393 p.

49 Pandolfo, J. P. et al. Prediction by Numerical Models of Transport and Diffusion in an Urban Boundary Layer. The Center for the Environment and Man, Inc. Final Report to E.P.A. under Contract CPA-70-62, July 1971, 139 p.

50 Bowne, N. E. and G. D. Robinson. A Regional Air Quality Simulation Model. The Research Corp. of New England: Report prepared under EPA Contract CPA 70-155, Sept. 1971, 35 p.

51 Fortak, H. G. Numerical Simulation of the Temporal and Spatial Distribution of Urban Air Pollution Concentration. In: Proceedings of Symposium on Multiple-Source Urban Diffusion Models, U. S. Env. Prot. Agency, APCO Publ. AP-86, 1970.

52 Worley, F. L. Sulphur Dioxide Reactions in the Atmosphere. In: Proceedings of the Second Meeting of the Expert Panel on Air Pollution Modeling, NATO Committee on the Challenges of Modern Society, Paris, July 1971.

53 Weber, E. Removal of Sulfur Dioxide from the Atmosphere. In: Proceedings of the Second Meeting of the Expert Panel on Air Pollution Modeling, NATO Committee on the Challenges of Modern Society, Paris, July 1971.

54 Weber, E. Contribution to the Residence Time of Sulfur Dioxide in a Polluted Atmosphere. J. Geophys. Res., Vol. 75, May 1970, p. 2909-2914.

55 Robinson, E. Critical Mathematical Evaluation of Air Pollution Concentration Modeling. Manuf. Chemists Assoc., Washington, D. C. 1970, 60 p.

56 Bowne, N. E. Space and Time Variability of SO_2 and Particulate Concentrations in Connecticut. The Research Corp. of New England: Report prepared under EPA Contract CPA 70-155, Sept. 1971, 62 p.

57 Hanna, S. R. A Simple Method for Calculating Dispersion from Urban Area Sources. J. Air Poll. Contr. Assoc., Vol. 21, Dec. 1971, p. 774-777.

Chapter XI

A SYNOPTIC-CLIMATOLOGICAL STUDY OF AIR POLLUTION POTENTIAL FOR ANKARA

by

Taskin Tuna

Deputy Director of Synoptic Division
Turkish Met. Office

Introduction

Ankara, capitol of Turkey, has been located on the central part of Anatolia. Its population has been increasing very rapidly especially during the last decade. The expansion of the city has brought very serious air pollution problems created by the combustion of smoke.

In Ankara the most of the emissions, a direct result of burning fuel, occurs during the day time and early evening in winter. The topography of the city differs widely from point to point that makes the problem very difficult and complicated.

Meteorology

The study of the types of air mass which affect the central part of Anatolia, namely Ankara, is rather complicated due to the irregular terrain. In winter, the cold core Sibirian anticylone (cp) causes decreasing temperature and produces snow from time to time. In winter, another source of air mass is maritime polar (mp) which may affect the northern and central part of Turkey. Depressions from the Mediterranean provide another source of active frontal conditions reaching the country in this season.

In winter, sometimes, Ankara has been experienced by high pressure systems which are associated with the warm ridge aloft. Under this condition subsidens and clear skies produce radiation inversion which is the most suitable factor for the creation of pollution. Light wind or calm condition may cause the pollutant unmoved in the lower atmosphere.

In summer, Turkey usually has been experienced by westerly current. During the summer months thermal low, being created on the Arabian desert may affect the central part of Turkey. Under this condition very warm and dry air prevails over Ankara (extreme temperature in summer in Ankara is 40°C).

The average wind speed is rather light (more than 50 percent of the wind speeds are below 1.5 m/sec).

From the meteorological standpoint, extensive and persistent high pollution potential areas are related to synoptic features and climatological conditions.

In the following paragraphs, some of the meteorological parameters will be discussed and their average values are given for Ankara. After being investigated, it will be shown that the meteorological elements for Ankara are the most effective and suitable in the creation of highest concentration.

The daily maximum mixing height is a useful measure in air pollution studies. It is readily determined as the height above the surface where the "adiabatic lapse - rate" from the surface maximum temperature intersects the observed vertical temperature profile.

The mixing height, usually varies diurnally, often being zero during the night because of radiational cooling of the ground and the deepest during the day, because of solar heating of the ground.

Figure 1 shows how the mixing height varies with the months for a period of nine years (1964-1972). The mixing height, as expected reaches its maximum value during summer months. An average mixing height of 1000 - 1200 meters during Spring and Autumn, on the other hand it may be considered auxiliary factors, among others, to hold the pollutants in the air suspended.

The surface based radiation inversion is frequently associated with high pressure systems. The radiation inversion is a nocturnal phenomenon associated with clear night time skies and light winds which are usually seen in Ankara under the above conditions.

The depth of inversion layer and temperature difference between top and bottom of the layer may also play an active role for the occurrence of pollution.

Figure 2 shows how the inversion layer varies with the months during a period of nine years. As seen from the figure, the thickness of the inversion layer during December, January and February is greater than the other months. One should not be surprised to see that there exists an increase in the pollutant concentration values in these months.

Figure 3 is related to the number of days with inversion. On the average, 18 days with inversion in October has a maximum value in comparison with the other months of the year. On the other hand, the number of the days with inversion in the other months varies between 8 to 10.

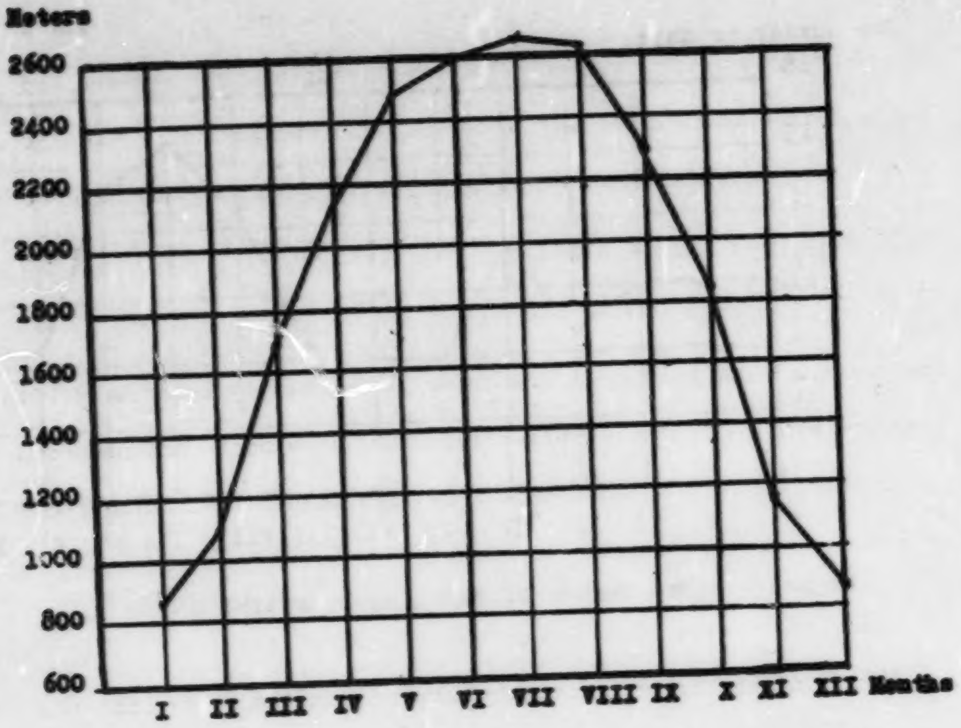


Figure I - The variation of average mixing height with months.

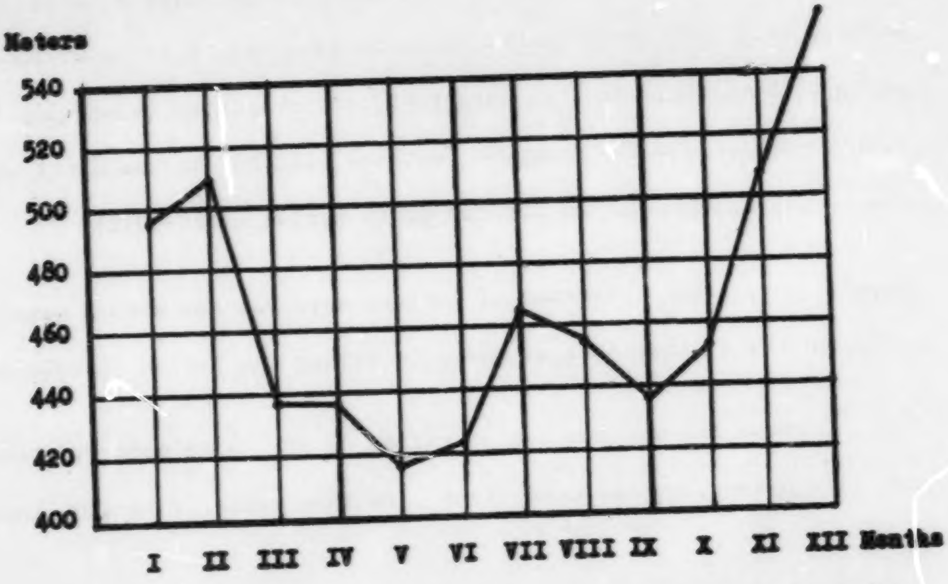


Figure 2 - The variation of average inversion height with months.

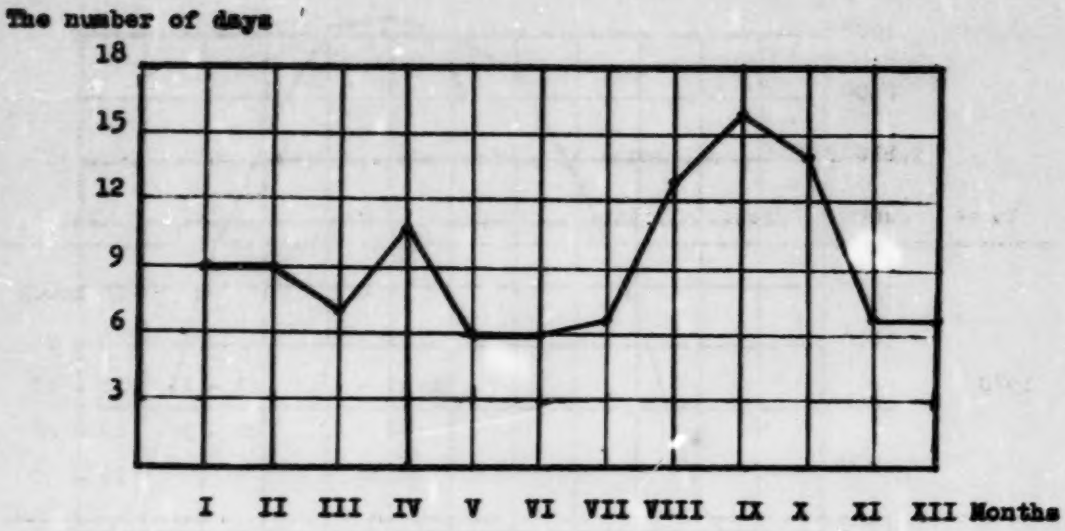


Figure - 3 The number of days (with inversion)

Synoptic Features Associated with High Pollution Potential.

In order to find out reasonable diffusion model, NATO had undertaken the "Ankara Air Pollution Research Project." In November 1970 the concentration data had been obtained from the 13 sampling stations located several parts of the city. In this paragraph, the relationship between the concentration amount and the synoptic features will be discussed for the winter and autumn months, during the two years period (1970-1972).

Table 1 shows the occurrence of surface anticyclones with a warm ridge aloft in the central part of Anatolia during the period of 1970-1972.

Table 2 shows the maximum concentration of SO_2 value occurred under the favorite meteorological conditions. In this table, inversion layer (L), Table - I The occurence of surface anticyclones (1970 - 1972).

Years	Jan.	Feb.	Mar.	Apr.	Oct.	Nov.	Dec.
1970					1 - 2	31 Oct- 5	29 Nov-2
					8 - 11	8	8 - 9
					17 - 18	13 - 16	14 - 16
					22 - 23	20 - 22	19 - 22
							28 - 30
1971	1 - 3	15 - 16	5 - 6	2	3 - 4	5 - 13	19 - 21
	5 - 6		8	6	9 - 17	19	28 - 3
	15 - 17		15	24	20 - 21		(Jan.1972)
	20 - 26		20 - 23	27-4May.	25 - 26		
	30 - 1Feb.		29 - 30		30		
1972	1 - 7	6 - 13	9 - 10	4 - 7			
	9 - 11	18 - 26	19				
	18 - 20		26 - 28				
	23 - 24		30 - 1Apr.				
	28 - 31						

Table -2. The concentration amount and the meteorological parameters. (1970 - 1972)

14 - 18 Nov. 1970

Max. conc. of SO_2 : 840 μgr/m^3 (occured on 15 - 16 Nov.)

The Dates	L(m)	$\Delta T(C^\circ)$	h(m)	$\bar{u}$(m/sec)	u.h	p	V_{500}
14 Nov.	900	1.3	1000	3.0	3000	1025	10
15 Nov.	400	2.8	700	2.5	1750	1020	10
16 Nov.	-	-	700	3.0	2100	1018	30
17 Nov.	250	1.2	1500	3.5	5250	1020	40
18 Nov.	-	-	1100	9.0	9000	1020	60

8 - 9 Dec. 1970 :

Max. conc. of SO_2 : 940 μgr/m^3 (occured on 8 - 9 Dec.)

8 Dec.	-	-	1500	6.5	9750	1026	50
9 Dec.	-	-	600	6.0	3600	1025	5
10 Dec.	-	-	1000	8.0	8000	1019	10

22 - 23 Dec. 1970 :

Max. conc. : 771 μgr/m^3 (occured on 22 - 23 Dec.)

21 Dec.	-	-	70	3.0	210	1024	40
22 Dec.	500	9.0	300	2.0	600	1025	20
23 Dec.	850	4.5	450	3.5	1575	1020	15
24 Dec.	-	-	400	3.5	1400	1016	10

27 - 28 Dec. 1970 :

Max. conc. : 540 μgr/m^3 (occured on 27 - 28 Dec.)

27 Dec.	-	-	150	6.0	900	1024	30
28 Dec.	-	-	320	2.0	640	1027	35
29 Dec.	-	-	400	2.0	800	1025	25

29 - 30 Dec. 1970 :

Max. conc. : 570 μgr/m^3 (occured on 29 - 30 Dec.)

Table - 2. (Continued)

The Dates	L(m)	$\Delta T(C^\circ)$	h(m)	$\bar{u}$(m/sec)	u.h	P	V_{500}
30 Dec.	500	3.3	400	4.0	1600	1026	35
31 Dec.	250	1.0	350	4.5	1575	1024	60
2 - 3 Jan. 1971 : Max. conc. : 987 $\mu gr/m^3$ (occured on 2 - 3 Jan.)							
2 Jan.	550	2.5	600	4.0	2400	1024	65
3 Jan.	350	6.0	180	2.5	450	1022	55
4 Jan.	580	4.0	520	7.0	3640	1023	65
15 -18 Jan. 1971 : Max. conc. : 417 $\mu gr/m^3$ (occured on 15 - 16 Jan.) 527 $\mu gr/m^3$ (occured on 16 - 17 Jan.) 495 $\mu gr/m^3$ (occured on 17 - 18 Jan.)							
15 Jan.	-	-	1000	7.0	7000	1025	15
16 Jan.	-	-	1100	2.5	2750	1023	20
17 Jan.	-	-	920	2.0	1840	1022	20
18 Jan.	-	-	1700	4.5	7650	1022	10
22 - 23 Jan. 1971 : Max. conc. 949 $\mu gr/m^3$ (occured on 22 - 23 Jan.)							
21 Jan.	450	1.6	1100	2.5	2750	1017	20
22 Jan.	350	2.2	820	2.5	2050	1018	10
23 Jan.	-	-	520	2.0	1040	1024	15
24 Jan.	480	6.0	400	2.5	1000	1023	10
25 Jan.	540	2.0	1100	4.0	4400	1022	20

23 - 25 Mar. 1971 :

Max. conc. : 386 $\mu gr/m^3$ (occured on 23 - 24 March)

and 192 $\mu gr/m^3$ (occured on 24 - 25 March)

Table - 2. (contiued)

The Dates		L(m)	$\Delta T(C^0)$	h(m)	$\bar{u}$(m/sec)	u.h	p	V_{500}
22 Mar.		-	-	2500	4.5	11250	1019	25
23 Mar.		-	-	1800	6.0	10800	1016	5
24 Mar.		-	-	1000	9.0	9000	1015	35
25 Mar.		-	-	850	7.0	5950	1011	35
8 - 10 Oct. 1971 :								
Max. conc. : 640 μgr/m^3 (occured on 8 - 9 Oct.)								
491 μgr/m^3 (occured on 9 - 10 Oct.)								
7 Oct.		-	-	1600	8.0	12800	1018	65
8 Oct.		-	-	1950	8.0	15600	1024	30
9 Oct.		-	-	1800	3.0	5400	1028	30
10 Oct.		400	2.5	1750	3.0	5250	1028	15
11 Oct.		600	3.0	1600	2.0	3200	1023	15
12 Oct.		-	-	2700	6.0	16200	1023	20
9 - 17 Nov. 1971 :	Max. Conc.							
8 Nov.	658	-	-	960	4.0	3840	1025	30
9 Nov.	500	780	2.3	1400	2.5	3500	1021	20
10 Nov.	1065	980	1.0	1400	7.5	10500	1024	25
11 Nov.	880	450	4.5	900	3.5	3150	1023	35
12 Nov.	840	750	5.7	780	7.0	5460	1022	30
13 Nov.	320	800	4.0	160	4.0	640	1017	45
14 Nov.	660	1150	2.5	700	10.0	7000	1017	50
15 Nov.	253	600	2.5	550	4.0	2200	1018	50
16 Nov.	365	-	-	700	4.0	2800	1017	15
17 Nov.		-	-	1000	5.0	5000	1014	15

18 - 21 Dec. 1971 :

Max. conc. : 479 μgr/m^3 (occured on 18 - 19Dec.)
479 μgr/m^3 (occured on 19 - 20 Dec.)

Table - 2 (continued)

T Dates	L(m)	$\Delta T(C^{o})$	h(m)	$\bar{u}$(m/sec)	u.h	p	V_{500}
1[illegible] Dec.	-	-	920	6.0	5520	1018	25
19 Dec.	-	-	220	2.0	440	1025	45
20 Dec.	-	-	0	0	0	1028	25
21 Dec.	-	-	0	0	0	1025	30
22 Dec.	-	-	1000	11.0	11000	1015	15

5 - 9 Jan. 1972 :

Max. conc. : 788 $\mu gr/m^3$ (occured on 5 - 6)
1072 $\mu gr/m^3$ (occured on 6 - 7)
877 $\mu gr/m^3$ (occured on 7 - 8)
616 $\mu gr/m^3$ (occured on 8 -9)

5 Jan.	-	-	1600	2.0	3200	1027	5
6 Jan.	1250	1.5	150	2.0	300	1028	25
7 Jan.	1100	2.5	500	4.0	2000	1028	20
8 Jan.	-	-	900	3.0	2700	1025	20
9 Jan.	500	1.5	1600	4.0	6400	1028	15
10 Jan.	550	2.5	1100	1.0	1100	1027	15

the temperature difference between the top and the bottom of the layer (ΔT), mixing height (h), average wind speed within the mixing height (u: m/sec), ventilation (u.h), surface pressure (p) and the wind speed (knots) (V_{500}) at 500 mb. are also shown:

The concentration amount, obtained from the four stations, shows the maximum value for the 24 hours.

Concluding Remarks

The source distribution and topography in the vincinity of the sampling and the wind field are the major factors which affect the concentration values. However, it is found that, the highest concentration occurring in the selected periods, is largely associated with the meteorological parameters, especially wind speed and stability. In this study, experience and investigation have shown that the light wind speed within the mixing height is the most effective element in the creation of high pollutant. Since Ankara is always the polluted city, the relative and rapid increase in pollution makes the problem very important.

In this work, inversion layer and the temperature differences of the layer have also been investigated, especially under the influence of a slowly moving warm core anticyclone.

As far as the forecasting of air pollution concentrations are concerned, the following rules can be applied for different concentration values in the Ankara region.

A. Concentration value: about 1000 ug/m^3:

(i) Ventilation must be ≤ 3000 m^2/sec (without inversion).

(ii) If inversion exists, ventilation must be ≤ 1500 m^2/sec.

(iii) Surface pressure (anticyclonic circulation) must be ≥ 1022 mb.

B. Concentration value: about 750 ug/m^3.

(i) Ventilation must be ≤ 4000 m^2/sec. (without inversion).

(ii) If inversion exists, ventilation must be ≤ 2000 m^2/sec.

(iii) Surface pressure (anticyclonic circulation) must be ≥ 1020 mb.

C. Concentration value: about 500 ug/m^3.

(i) Ventilation must be ≤ 5000 m^2/sec. (without inverstion).

(ii) If inversion exists, ventilation must be ≤ 2500 m^2/sec.

(iii) Surface pressure (anticyclonic circulation) must be ≥ 1020 mb.

The above rules will be applied for the next autumn and winter for Ankara. If the verification degree of forecasting is satisfactory, forecasting of air pollution concentrations is going to be made.

References

1. Holzworth, G. C., A Study of Air Pollution Potential for the Western United States, J. of Applied Meteorology, September 1962.

2. Niemeyer, L. E., Forecasting Air Pollution Potential, Mon. Wea. Rev. Vol. 88, p. 88.

3. Turkish Met. Office, Daily series, synoptic weather maps.

4. WMO, Technical Note No. 121, Dispersion and Forecasting of Air Pollution, 1972.

5. WMO, Technical Note No. 106, Meteorological Aspects of Air Pollution, 1970.

Chapter XII

ON THE SELECTION OF SITES OF
AIR POLLUTION SAMPLING STATIONS

Suha Selamoglu*

Mechanical Engineering Department
The Middle East Technical University
Ankara, Turkey

---

* On assignment to the NATO/CCMS Panel on Modeling by the Turkish Scientific and Technical Research Council

ON THE SELECTION OF SITES OF AIR POLLUTION SAMPLING STATIONS

Two main objectives in setting up stations to obtain quantitative data on the actual air pollution in an urban area are the following.

1. The data are interpreted as a measure of danger to which the receptors (humans, etc.) are actually exposed.

2. The data are used as a calibration standard for the model which is being developed to estimate pollutant concentrations in the area.

The geographical locations of the sampling stations may affect the reliability in the attainment of either goals. If the number of stations a city can afford is a few the decision on locality may very well be done on empirical grounds as given, for example, by Mahoney et al. (see the reference) or elsewhere. If the number of stations is large their distribution should better be based on quantitative grounds which may be more reliable or complementary to the empirical considerations. In the following a criterion will be presented according to which an optimum distribution may be obtained by way of comparisons among various geographical distributions of stations.

Different distributions will arise from different considerations pertaining to the use of the measurement data. An optimum distribution of stations which is dictated by certain objective may not be optimum so far as the other objectives are concerned. For example, a certain distribution may satisfy the needs of a modelist who merely concentrates on whether his model is able to predict the pollution at reasonably dispersed points over an area. But it may not be the best distribution from the point of view of public health if in the most polluted subregions there are no stations at all. Furthermore, different pollutant species may give different optimum distributions.

The idea to be followed is to render minimum the error in estimating the measure of a certain entity which characterizes the use of the data by a proper distribution of sites.

1. The measure of danger in an area A due to a pollutant p may be defined somewhat arbitrarily by the following quantity which may be called the "severity level of p".

$$SL_p = \frac{1}{\bar{C}_{pr} A} \int_A W_p(x,y)\, \bar{C}_p(x,y)\, dA \qquad (1)$$

where A is the entire area in consideration, $\bar{C}_p$ is the actual concentration of p averaged over a given time interval, W_p is a dimensionless weight function which emphasizes or deemphasizes the danger depending upon the population density at point (x,y), the averaging time, the pollutant in question, the frequency distribution of pollutant concentrations, and perhaps other factors. $\bar{C}_{pr}$ is a reference concentration of pollutant p (for example, the maximum tolerable concentration value).

One can only make an estimate (through the data obtained from measurements) of the severity level. Let there be n stations located at points (x_j,y_j), $j = 1,2,\ldots,n$. The concentrations at points (x,y) are estimated as $\bar{C}_p'$ by a suitable algorithm using measured (and averaged) concentrations $\bar{C}_{pj}$. Hence,

$$\bar{C}_p' = \bar{C}_p'(x,y;\, \bar{C}_{pj}),\ j = 1,\ldots,n \qquad (2)$$

and it is not equal to $\bar{C}_p$. One would then estimate the severity level as

$$SL_p' = \frac{1}{\bar{C}_{pr} A} \int_A W_p(x,y)\, \bar{C}_p'(x,y;\bar{C}_{pj})\, dA. \qquad (3)$$

The goal should be to make the difference between SL_p' and SL_p minimum for all possible areas. Thus, for example,

$$e_p = \frac{1}{\bar{C}_{pr}\,A} \int_A W_p(x,y) \left| \bar{C}_p'(x,y;C_{pj}) - \bar{C}_p(x,y) \right| dA \qquad (4)$$

or another suitable expression, should be minimized by varying (x_j,y_j). The process is clearly impractical, but one can pick among a number of proposed distributions (say by using empirical criteria) the one which minimizes e_p, although it would not be the absolute minimum.

One can write the last expression in form

$$e_p(x_j,y_j) = \frac{1}{C_{pr}\,A} \int_A W_p \left| \Delta\bar{C}_p \right| dA \qquad (5)$$

where

$$\Delta\bar{C}_p = \bar{C}_p'\left[x,y;\ \bar{C}_{pj}(x_j,y_j)\right] - \bar{C}_p(x,y)\ . \qquad (6)$$

$\Delta\bar{C}_p$ contains various errors. Some of the errors are introduced by C_{pj}, i.e., the measured values of concentrations such as the instrumental errors, reading errors, errors due to the geographical locality of the measuring instrument, etc.. A second type of errors come in through the unavoidable approximations due to inter- or extrapolations in calculating $\bar{C}_p'(x,y)$ from $\bar{C}_{pj}(x_j,y_j)$. Since $\bar{C}_p'$ are known but $\bar{C}_p$ are not the major problem here is in obtaining reliable estimates of the distribution of $\Delta\bar{C}_p$ over the area for each possible (or proposed) arrangement of n stations.

The procedure may be extended to the case where m pollutant species occur simultaneously. The quantity to be minimized may then be taken as

$$e = \sum_{p=1}^{m} e_p\ . \qquad (7)$$

It may be noted that the severity level may easily be made to reflect the potential danger exhibited by certain pollutants when concentration or concentration times the duration of exposure exceeds certain predetermined limits. In this case, the integrand $W_p\overline{C}_p$ in the expression for SL_p should be replaced by

$$W_p\overline{C}_p = \int_0^{\infty} w_p(x,y;C_p,f_pC_p)\, f_p(C_p)\, dC_p(x,y) \; , \qquad (8)$$

where f_p is the frequency function of concentration C_p and w_p is the weight function which depends on concentration times its frequency of occurrence (exposure) as well as on concentration. It may be given the value of infinite, for example, in order to express the seriousness of the situation whenever C_p or f_pC_p exceeds predetermined limits.

2. When the objective is to improve a given model a similar approach may be made. The model-estimated values, $\overline{C}_{pm}$, are to be compared with the actual ones, $\overline{C}_p$. But since $\overline{C}_p$ are not known the former are compared with $\overline{C}_p'$ instead. The comparison gives a measure of departure of the model from reality, and improvements are effected in order to reduce this departure. The best improvement is possible only when the discrepancy between the actual and measured pollutant concentrations is minimum. However, one can again introduce a weight of importance to the success or failure of the model which may be made to differ from one point to the other as well as from one state of pollution to the other.

Depending on the mode of use of the model-estimated data the weight function may be modulated at will. For example, if the model is to be used to predict the severity level the problem is then equivalent to the previous one with the same weight function W_p. It should be noted that the quantity to be minimized here has nothing to do with the model-estimated concentrations $\overline{C}_{pm}$. Ideally, the latter would, in the limit, coincide with the concentrations $\overline{C}_p'$

if a perfect model were attained. On the other hand, if the quantity

$$\frac{1}{\bar{\bar{C}}_{pr}\; A} \int_A W_p \left| \bar{C}_{pm} - \bar{C}_p' \right| dA \qquad (9)$$

were made minimum, this process would adjust the n stations geographically to give the best agreement with the existing model data, which is not perfect yet. Obviously, this should not be the goal. Hence the quantity to be minimized is again

$$e_p = \frac{1}{\bar{\bar{C}}_{pr}\; A} \int_A W_p \left| \bar{C}_p' - \bar{C}_p \right| dA \,, \qquad (10)$$

but now with a different understanding of the weight function W_p which is motivated by the model use.

Reference

J.R. Mahoney, W.O. Maddaus, and J.C. Goodrich, "Analysis of Multiple-Station Urban Air Sampling Data", Proc. of the Symposium on Multiple-Source Urban Diffusion Models, U.S. Environmental Protection Agency, 1970, pp. 11.1-11.22.

Chapter XIII

DETERMINATION OF THE ATMOSPHERIC TEMPERATURE AND DENSITY PROFILES FROM FREE DESCENT OR ASCENT OF A SPHERE OF CONSTANT VOLUME AND MASS

Suha Selamoglu*

Mechanical Engineering Department
The Middle East Technical University
Ankara, Turkey

---

* On assignment to the NATO/CCMS Panel on Modeling by the Turkish Scientific and Technical Research Council

DETERMINATION OF THE ATMOSPHERIC TEMPERATURE AND DENSITY PROFILES FROM FREE DESCENT OR ASCENT OF A SPHERE OF CONSTANT VOLUME AND MASS

Introduction

The knowledge of the vertical temperature variation in the lower atmosphere is of particular importance in air pollution calculations since it is closely related to the mixing depth. The temperature, density and pressure of the atmosphere are interrelated. Under reasonable assumptions the information on one of them, e.g., density, may be sufficient to determine the others. As it will be shown subsequently, the density profile of the atmosphere may be related to the velocities which would be acquired by a spherical body in its free fall or ascent in the atmosphere. Provided that the velocity history of such sphere is recorded with sufficient accuracy this information can be translated to give the density, temperature, and pressure profiles of the atmosphere. The practical value of the method, which needs experimentation, will not be discussed although the calculations show some promise. The method may be considered as an extended application of pilot balloons which have been used extensively to determine the wind velocities [1] . However, the latter are not suitable for the prediction of temperature because of their uncontrollable volume and mass.

Analysis

Consider a sphere which is maintained at constant volume and constant mass. It can be shown that a terminal velocity of the order of 3 m/s is reached within one percent in less than 4 seconds by a sphere of about 1 m diameter. It will, therefore, be assumed that the sphere is, in its free slow descending or ascending motion, at equilibrium under the forces of gravity, buoyancy, and drag. Hence,

$$(\rho_s-\rho_a)Vg = \pm CA\frac{\rho_a}{2}v^2 \quad \left\{\begin{array}{l} + \text{ for ascending sphere} \\ - \text{ for descending sphere}\end{array}\right\} \qquad (1)$$

where ρ_s is the apparent uniform density of the sphere, ρ_a is the density of the atmosphere, V and A the volume and the projectional area of the sphere, g gravitational acceleration, C drag coefficient, and v the terminal velocity of ascent or descent (for a more general discussion see p. 40ff. of Ref. 1). With constant mass and volume, ρ_s, V, A are constant. C may also be taken as constant since its variation with v is negligible [2] ; the variation of g with height may also be neglected. Consequently, ρ_a is determined from (1) as

$$\rho_a = \rho_s \Big/ \left(1 \pm \frac{1}{2}\cdot\frac{Cv^2}{gV/A}\right). \qquad (2)$$

If $v(z)$ can be measured at any altitude z the density $\rho_a(z)$ of the atmosphere at the same altitude is found from (2).

The temperature distribution $T(z)$ can be determined from density. The equation of state for unsaturated humid air may be written as [3]

$$\rho_a(z) = p(z) / RT_v(z) \qquad (3)$$

where R is gas constant, p is pressure and T_v is the virtual temperature defined by

$$T_v(z) = T(z)\left(1 + 0.378\frac{e_0}{p_0}e^{-\frac{z}{\beta}}\right) \qquad (4)$$

in terms of the actual temperature T, partial vapor pressure e_0 and pressure p_0 at the ground level $z=0$. β is a constant, approximately 5000m. The pressure $p(z)$ can be calculated from the density distribution by assuming static equilibrium of the atmosphere.

$$p(z) = p_0 - \int_0^z \rho_a(z)\,g(z)\,dz. \qquad (5)$$

From (2), (3), (4), and (5) $T(z)$ may be solved. The expressions can be nondimensionalized by introducing certain dimensionless parameters. Let

$$\left.\begin{aligned} & r=\rho_a/\rho_0 \ , \ r_{sc}=\rho_s/\rho_0 \ , \ \alpha=g_0 H/RT_0 \ , \ \zeta=z/H \ , \\ & t=T_0/T \ , \ t_v=T_0/T_v \ , \ \varphi=v/v_0 \end{aligned}\right\} \tag{6}$$

where subscript o denotes the value at the ground level and H is some reference height. Clearly,

$$v_0=\sqrt{\frac{2g_0 V/A}{C}\left|1-r_{sc}\right|} \ . \tag{7}$$

Now, from (2), (3), (4), and (5)

$$r(\zeta)=r_{sc}/\left[1 \pm \varphi^2(\zeta)\right] \tag{8}$$

or

$$r(\zeta)=t_v(\zeta)\,\frac{\frac{p_0}{\rho_0}-g_0 H\int_0^{\zeta} r(\zeta)\,\frac{g(\zeta)}{g_0}\,d\zeta}{RT_0}=t_v(\zeta)\left[1-\alpha\int_0^{\zeta} r\,\frac{g}{g_0}\,d\zeta\right] . \tag{9}$$

On elimination of $r(\zeta)$ between the last two expressions and solving for $t_v(\zeta)$ one obtains

$$\frac{T_v(\zeta)}{T_0}=\frac{1}{t_v(\zeta)}=\frac{1}{r_{sc}}\left[1 \pm \varphi^2(\zeta)\right]\left[1-\alpha r_{sc}\int_0^{\zeta}\frac{g(\zeta)}{g_0}\,\frac{d\zeta}{1 \pm \varphi^2(\zeta)}\right] . \tag{10}$$

The actual temperature distribution may be found from (4) and (10) but the difference between T_v and T is quite small in general. In order not to complicate the algebra it will be assumed that $T \cong T_v$ and $g(\zeta) \cong g_0$. Then,

$$\frac{1}{t(\zeta)} \cong \frac{1}{r_{sc}}\left[1 \pm \varphi^2(\zeta)\right]\left[1-\alpha r_{sc}\int_0^{\zeta}\frac{d\zeta}{1 \pm \varphi^2(\zeta)}\right] . \tag{11}$$

It is clear that if $\varphi(\zeta)$ is known $t(\zeta)$ can be determined from (11) (or, better, $T(z)$ can be determined from (10) and (4)).

For the purpose of demonstration the reverse operation will now be applied. Namely, the temperature distribution $t(\zeta)$ will be assumed to be given. The resulting free ascent or descent velocity of the sphere will be sought. The calculations yield in this case

$$\varphi(\zeta)=\left|\frac{1}{1-r_{sc}}-\frac{r_{sc}}{1-r_{sc}}\cdot\frac{\exp\left[\alpha\int_0^{\zeta} t(\zeta)\,d\zeta\right]}{t(\zeta)}\right|^{1/2} , \tag{12}$$

or,

$$\varphi(\zeta) = |\, a - b\, E(\zeta) \,|^{1/2} \tag{13}$$

where

$$a = 1/(1-r_{s0}) \,,\; b = a r_{s0} \,,\; E(\zeta) = \frac{1}{t} \exp\left[\alpha \int_0^{\zeta} t \, d\zeta\right] . \tag{14}$$

Various temperature profiles may be assumed. Typically, a profile that varies linearly with elevation with one possible change in its slope is general enough for the purpose, temperature inversion being a special case of it. Selecting H to be the height at which the rate switches from m_1 to m_2 , one can write

$$\left.\begin{aligned} \frac{1}{t_1(\zeta)} &= 1 - \frac{m_1 H}{T_0}\zeta &&, \zeta \leq 1 \\ \frac{1}{t_2(\zeta)} &= 1 - (m_1 - m_2)\frac{H}{T_0} - \frac{m_2 H}{T_0}\zeta &&, \zeta > 1 \end{aligned}\right\} \tag{15}$$

which yield, on the condition that $m_1 \neq 0$, $m_2 \neq 0$,

$$\left.\begin{aligned} E_1(\zeta) &= \left(1 - \frac{m_1 H}{T_0}\zeta\right)^{1-\frac{g_0}{m_1 R}} &&, \zeta \leq 1 \\ E_2(\zeta) &= \left[1 - (m_1 - m_2)\frac{H}{T_0} - \frac{m_2 H}{T_0}\zeta\right]^{1-\frac{g_0}{m_2 R}} \left(1 - \frac{m_1 H}{T_0}\right)^{\frac{(m_1 - m_2) g_0}{m_1 m_2 R}} &&, \zeta > 1 \end{aligned}\right\} \tag{16}$$

In particular, when temperature remains constant over some interval of ζ , one obtains the following.

i. $m_1 = 0$, $m_2 \neq 0$,

$$\left.\begin{aligned} E_1(\zeta) &= e^{\alpha\zeta} &&, \zeta \leq 1 \\ E_2(\zeta) &= e^{\alpha}\left[1 - \frac{m_2 H}{T_0}(\zeta - 1)\right]^{1-\frac{g_0}{m_2 R}} &&, \zeta > 1 \end{aligned}\right\} \tag{17}$$

ii. $m_1 \neq 0$, $m_2 = 0$,

$$\left.\begin{aligned} E_1(\zeta) &= \left(1 - \frac{m_1 H}{T_0}\right)^{1-\frac{g_0}{m_1 R}} &&, \zeta \leq 1 \\ E_2(\zeta) &= \exp\left[\alpha \frac{\zeta - 1}{1 - m_1 H/T_0}\right]\left(1 - \frac{m_1 H}{T_0}\right)^{1-\frac{g_0}{m_1 R}} &&, \zeta > 1 \end{aligned}\right\} \tag{18}$$

iii. $m_1 = m_2 = 0$ (constant temperature, $T = T_0$),

$$E(\zeta) = e^{\alpha\zeta} \text{ for all } \zeta \geq 0 \,. \tag{19}$$

r_{s0} represents the weight of the sphere relative to the weight of air occupying the same volume. Its effect on the sensitivity of the method may be shown by taking four values, r_{s0} = 0.5, 0.9, 1.1, and 2.0, and evaluating the results for two different temperature profiles, namely, $m_1 = m_2 = 0.0098$ (dry adiabatic lapse rate) and $m_1 = m_2 = 0$ (constant temperature). The remaining data were chosen as $g_0 = 9.80$ m/s, $T_0 = 300^{\circ}$K, $R = 2.87 \cdot 10^6$ erg/g.°K, $H = 1000$ m .

Results

The following information can be gathered from the plots of φ vs. ζ as shown in Fig. 1.

i. When r_{s0} is not sufficiently small the ascending motion of the sphere ceases at a shallow height ζ_c . For $\zeta > \zeta_c$ descending motion is the only possible mode.

ii. The variation of φ with height as well as with m is greater, hence the sensitivity is better, the closer is r_{s0} to unity. In view of i., it is obvious that an ascending sphere (i.e., $r_{s0} < 1$) is not practical.

iii. The greater sensitivity that might be achieved by making r_{s0} as close to unity as possible is impaired by the fact that the duration of the descent (or ascent) becomes very long as the velocity $v = v_0 \varphi$ is smaller. A compromise must be reached for optimum use of the method.

iv. For descending sphere the velocity profile is nearly linear. However, considerable nonlinearity may be expected for $r_{s0} < 1.1$.

Figures 2 a, b compare velocity profiles that would be obtained with different temperature profiles for $r_{s0} = 1.1$ (descent) and $r_{s0} = 0.9$ (ascent). The following additional observations are worth mentioning .

v. A sudden change in the slope of the temperature profile is associated with a sudden change in slope at the same height of the velocity profile. This property is important since it indicates the height at which inversion

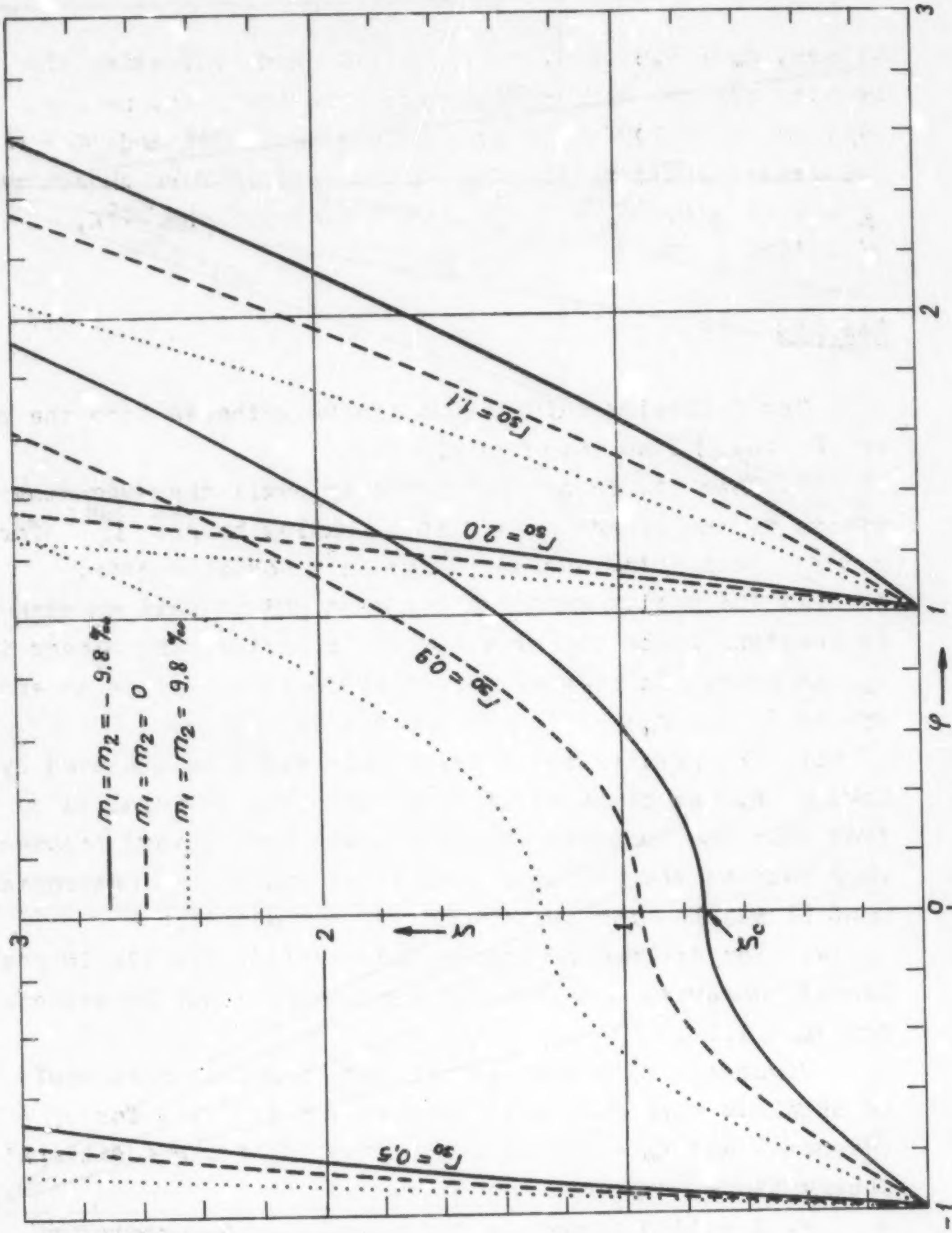


Figure 1. Velocity acquired by a constant volume sphere in free ascent and descent in the atmosphere

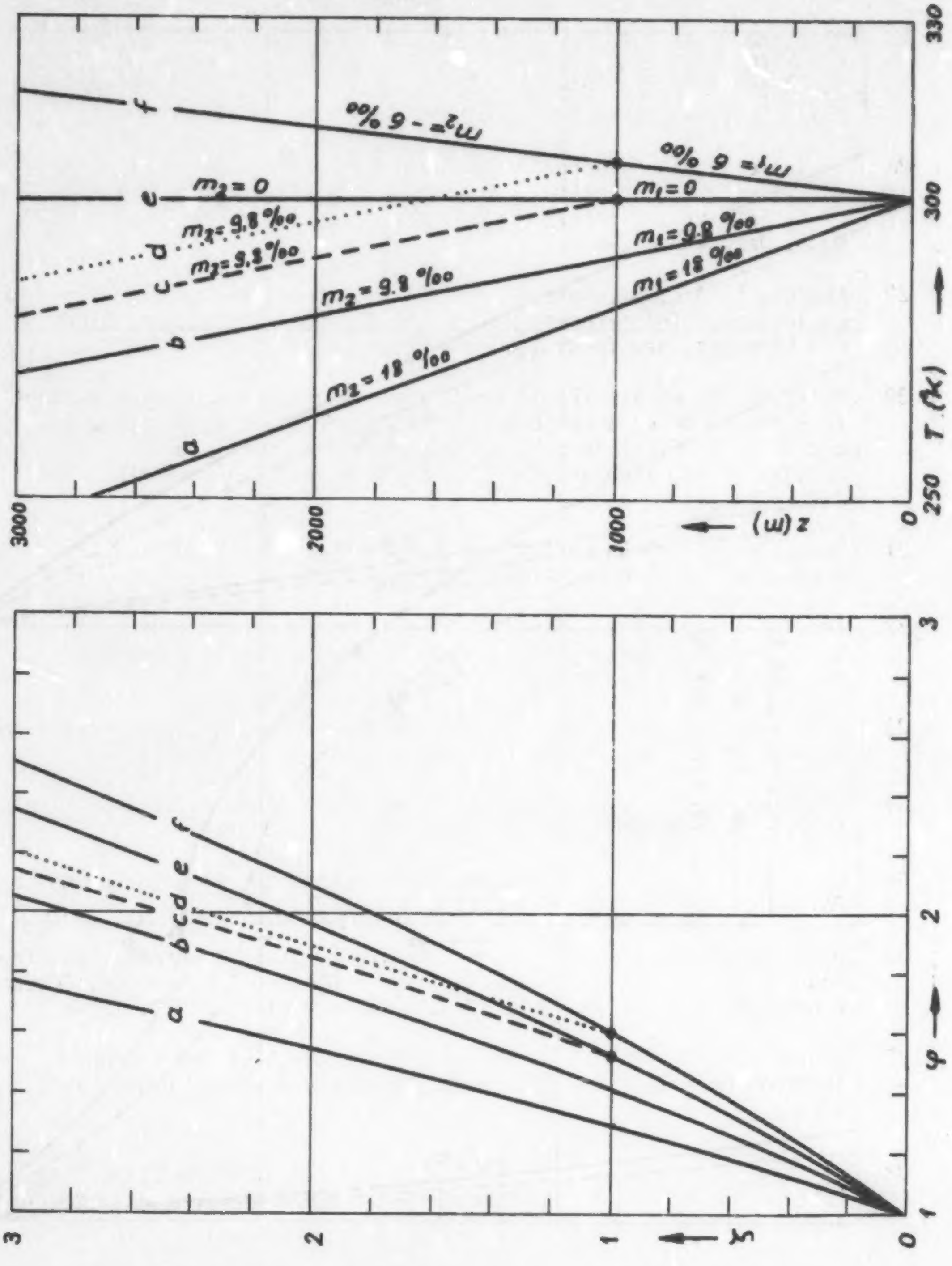


Figure 2a. Velocity of descent of a constant volume sphere with r_{so} = 1.1 under different atmospheric temperature profiles

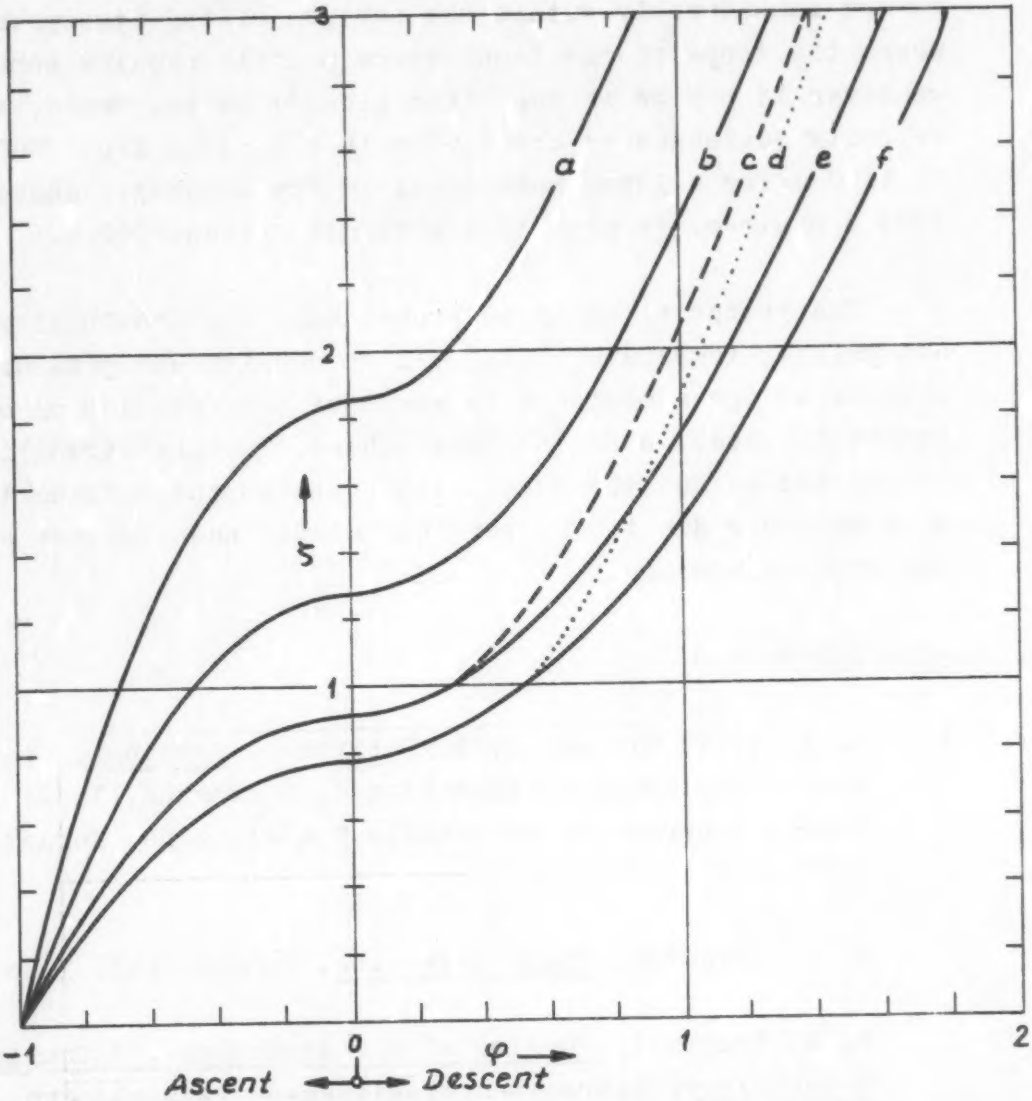


Figure 2b. Velocity of free motion of a constant volume sphere with r_{so} = 0.9 under different atmospheric temperature proliles (temperature profiles are the same as shown in Fig. 2a)

occurs.

vi. The slope of the velocity profile seems to be preserved considerably within the portion of the atmosphere where the slope of the temperature profile remains constant whatever it may be in the other (lower) parts. Hence, e.g., velocity decreases by about 5% with a descent from 2000 m to 1800 m for a lapse rate equal to dry adiabatic above 1000 m whatever it may be at altitudes below 1000 m.

The preceding analysis proves only the possibility of determining temperature (as well as density and pressure) profile of the atmosphere by means of the free motion of a constant volume, constant mass sphere. The practicability of the method and the associated problems and difficulties, such as those due to the vertical winds, need further study and experimentation.

References

1 V. A. Belinskii and V. A. Pobiyakho, Aerology, Gidrometeorologicheskoe Izdatel'stvo, Leningrad, 1962, Israel Program for Scientific Translations, Jerusalem, 1967

2 V. L. Streeter, Fluid Mechanics, McGraw-Hill, 1966

3 P. N. Tverskoi, Physics of the Atmosphere, A Course in Meteorology, Gidrometeorologicheskoe Izdatel'stvo, Leningrad, 1962, Israel Program for Scientific Translations, Jerusalem, 1965

Chapter XIV

AIR POLLUTION EPISODES AND MATHEMATICAL MODELS

BY

C. A. Velds

Royal Netherlands Meteorological Institute
De Bilt, the Netherlands

Introduction

Commonly used mathematical models for the calculation of long-average concentration profiles need average values of the emissions and of the meteorological parameters (viz. wind direction, wind speed, mixing height, stability) as an imput. During so called air-pollution episodes, lasting some days, when high concentrations or large nuissance to the population occur the meteorological circumstances differ considerably from the mean values. Apart from the question whether it is possible to give an estimation of the emissions during the air-pollution episodes, the concentrations are largely dependent on small changes in the wind and the rate of vertical exchange (inversion heights, mixing height).

In order to get an estimate of the concentrations during air-pollution episodes, at least mixing height and fumigation effects should be taken into account, supposing that the effective heights of the most important emissions are known. Of course the non-validity of the Gaussian plume model in light and variable winds is more serious. So it is doubtful whether mathematical models can be used for short period predictions of concentration profiles and warnings of air pollution episodes. Moreover it appears that there is no relation between the concentration level of the most commonly measured air pollution component sulfur dioxide and the nuissance to the public (bad smells, eye irritation).

In this study an analysis is given of an air pollution episode (15 September-4 October 1971) in the heavily industralized area around Rotterdam (called "Rijnmond" as it is situated along the mouth of the river Rhine) in the western part of the Netherlands. This episode has been called serious, not because of the concentration levels of the measured air pollution components, which were not extremely high, but because of the large number of complaints of eye irritation and bad smells that has been registered by the "Rijnmond Authority." On account of the nuissance experienced by the population, the government decided that an investigation should be made which air pollution components are responsible for the nuissance. This autumn a project started in which, for a period of 3 years, many air pollution components (nitrogen oxides, ozone, sulfur dioxide, carbon monoxide, different hydrocarbon compounds, particulate matter and hydrogen fluoride) will be measured to look for a relation of concentrations to complaints of eye irritation and bad smell.

Meteorological Circumstances

During the period between 15 September and 4 October 1971, circulation types with an anticyclonic area over Central Europe (HM) and with a ridge of high pressure extending from the Atlantic Ocean to Central Europe (BM) were the dominating weather patterns.

These anticyclonic circulation types are associated with sunny weather, light winds and an area of slowly descending air. The whole period can be divided in two periods with these circulation types (16th - 23rd September BM and 29th September - 3rd October HM) separated by a period with a westerly circulation and stronger winds.

The vertical temperature soundings of the radiosonde station at De Bilt (50 km ENE of Rotterdam) and measurements of the vertical temperature gradient along the 80 m-high meteorological tower at Vlaardingen (8 km W of Rotterdam) showed that during every night a surface inversion developed, except on 24, 25, 27 and 30 September, when the temperature gradient near the surface was nearly isothermal.

The daily mean wind speed at 10 m altitude was less than 2 m/s on the following days:

16 September	1.4 m/s	29 September	1.8 m/s
19 September	1.0 m/s	2 October	1.1 m/s
20 September	1.4 m/s	3 October	1.6 m/s
21 September	1.1 m/s		

To have another criterion for the stability in the lowest layer of the atmosphere Pasquill's stability classes have been estimated, based on the hourly measurements of cloud cover and wind speed at the 10 m level at the airport of Rotterdam. It appeared that in the period considered the frequency of stable and unstable classes was higher than "normal," of which the first occurred at night and the latter in the daytime, due to the strong insolation.

Measurements of SO_2

As a measure for the air pollution level the SO_2 concentrations of the 31 sampling sites of the automatic monitoring network in the Rhinemond were used. Generally the hourly concentrations were less than 200 ug/m^3 at night, except on 28-29 and 29-30 September. Besides that many stations had hourly values of the SO_2 concentration less than 50 ug/m^3. Apparently the SO_2 emissions from high stacks did not reach the ground because of the surface inversion and the emission of low sources was not important.

Fumigation

On some days there were clear fumigation effects. At night the SO_2 was emitted in the stable inversion layer, which prevented contact with the ground. In the morning the radiation inversion was broken-down from the ground upward due to the insolation. When the unstable layer reached plume level, the compact plumes began downward diffusion leading to high ground level concentrations. During the fumigation period the number of stations with a concentration above 200 ug/m^3 increased on 12 of the 20 days, as can be seen in Table 1. This table also shows that on every morning of the period with an unstable temperature gradient fumigation occurred when the mixing height became larger than 80 m, except on the 19th and 29th of September.

Apparently the SO_2 emission from high stacks (higher than 80 m) comes down through the violent turbulence in the mixing layer during fumigation conditions.

On the 19th of September there is no pronounced fumigation effect, probably due to the fact that the mixing height rises quickly to a level of more than 1000 m within one hour. On the 29th September the SO_2 concentrations were already high at 8:00 A.M., presumably because of advection of air rich in SO_2, which passed in the night with NE winds and returned in the morning with a wind veering to the south.

On the 1st of October the fumigation conditions consisted for a long time with a neutral stratification in the morning, which became unstable at noon when the sun broke through.

The mean daily variation (shown in Figure 1) of the SO_2 concentration, averaged over all 31 sampling sites shows clearly the increase in SO_2 concentration during the fumigation period from 11:00 to 13:00 hours.

Influence of the Mixing Height

On the 23rd of September high SO_2 concentrations were found during neutral stability until 13:00 P.M., but with a very low mixing height of 200 m and a mixing volume of 800 m2/s. When the mixing height increased, the concentration decreased.

TABLE 1

Date	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
15 Sept.	8.00	600	> 2000	3.5	extremely/moder.unstable	2	-	< 100
16 "	9.00	1000	1700	2.0	extr. unstable	3	61	129
17 "	8.30	400	1400	3.5	moder. unstable	6	66	228
18 "	8.00	200	900	6.0	slight unstable	2	51	125
19 "	9.00	1000+	2000	2.5	moder. unstable	0	70	162
20 "	9.30	600	1700	1.0	extr. unstable	3	70	387
21 "	10.00	1000	1400	1.5	extr. unstable	11	111	592
22 "	9.30	200	1000	3.0	moder. unstable	7	94	573
23 "	8.30	200	600	4.0	slight unstable	2	88	880
24 "	8.30	400	500	6.0	neutral	-1	42	159
25 "	9.00	600	600	5.0	neutral	0	45	95
26 "	10.30	1000	1000	6.0	neutral	0	53	188
27 "	7.00	400	700	5.5	neutral	0	54	320
28 "	9.00	500	1400	2.0	moder. unstable	1	74	392
29 "	10.30	900	1100	2.0	moder. unstable	-5	114	1022
30 "	8.30	400	600	5.5	neutral	-3	69	437
1 Oct.	8.30	200	1100	3.5	neutral	2	72	479
2 "	10.00	200	600	1.0	extr. unstable	6	104	442
3 "	10.30	400	1100	2.0	neutral/unstable	6	78	1042
4 "	7.00	200	1200	6.0	neutral	0	48	97

(1) Time T when the mixing height rises to 80 m.
(2) Mixing height one hour later than T (in m).
(3) Maximum mixing height (in m).
(4) Average wind speed over mixing layer at time T (in m/s).
(5) Stability in the hour before and after T.
(6) Increase in the number of stations with a concentration larger than 200 $\mu g\ SO_2/m^3$ one hour after T.
(7) Daily mean value of the SO_2 concentration of the 31 measuring sites (in $\mu g/m^3$).
(8) Total number of complaints.

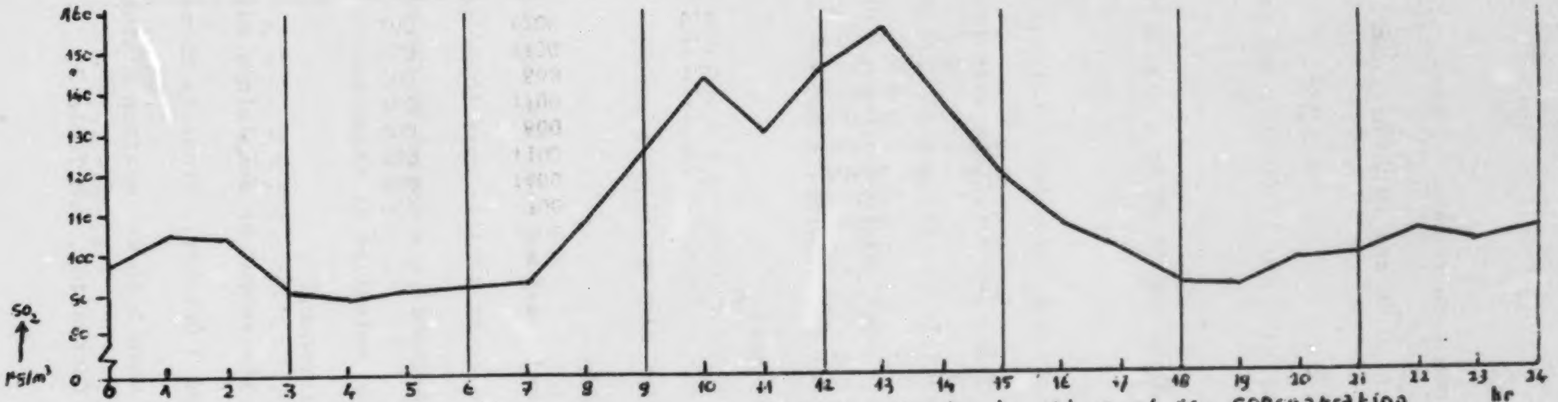


Fig.1 Mean hourly values of SO_2 concentration

figure 3

High SO_2 concentrations were found on 3 days, viz.

21st September between 10:00 and 18:00 hr., max. mixing volume 3500 m2/s.

29th September between 9:00 and 17:00 hr., max. mixing volume 2200 m2/s.

2nd October between 10:00 and 16:00 hr., max. mixing volume 1200 m2/s.

These situations are characterized by a small maximum mixing volume and unstable situations. The high concentrations were found to decrease at the end of the day when the unstable stratification turned to a stable one. 24 and 25 September had also small mixing volumes, 2200 and 3000 m2/s respectively, but low SO_2 values, apparently because of the neutral stability due to high wind speed.

Complaints of Bad Smells

The "Rijnmond Authority" kindly placed a survey of complaints on bad smells at our disposal (Table 1).

Most complaints were made between 6:00 A.M. and noon, the number of complaints in the afternoon being considerably lower than in the morning. So it appeared that the complaints are caused by the emissions of low and moderately high sources, the emissions of these sources can be dispersed sufficiently only in the afternoon.

It is remarkable that the amount of complaints was very large on 21, 22, 23, 29 September and 3 October. Probably there is an accumulation affect on 21-23 September, when both the maximum mixing height and the maximum mixing volume were decreasing, see Table 2.

TABLE 2. Mixing height, mixing volume and number of complaints

date	Maximum mixing height (m)	Maximum mixing volume (m2/s)	Number of complaints between 6-12 AM	between 12-18 PM
20 Sept.	1700	6000	199	60
21 Sept.	1400	3500	328	161
22 Sept.	1000	4000	233	195
23 Sept.	600	3000	542	236

The large number of complaints on 29 September occurred on the first day of the second period with stagnating weather, when the maximum mixing volume was again less then 2500 m2/s. The large number of complaints on the 3rd October appears to have a retarded effect as one day earlier the lowest ventilation factor occurred.

The relation between the number of complaints and the height of the mixing layer led us to examine this relation further.

The meteorological situation of the days with more than 100 or 200 complaints respectively has been analysed for the period 1 January - 12 October 1971. Although the number of complaints of bad smells is a subjective system for the definition of an air pollution level, there is clearly a relation with the height of the maximum mixing layer. On 23 of the 32 days with more than 100 complaints the maximum mixing height was less than 1000 m. The criterion for the occurrence of complaints can be tightened up by taking also the daily mean wind speed in the mixing layer.

The result is that more than 200 complaints were made on days with a mixing height less than 500 m and mean wind speed $\leq$ 4.5 m/s, mixing height between 500 and 1000 m and mean wind speed $\leq$ 2.5 m/s, mixing height between 1000 and 1500 m and mean wind speed ≤ 2 m/s, mixing height larger than 1500 m and mean wind speed ≤ 1.5 m/s. When the ventilation factor is less than 3000 m2/s there is a chance that the number of complaints increases.

Conclusion

The study of the relation between meteorological parameters, the SO_2 concentration and the nuissance experienced by the public during and air pollution episode leads to the conclusion that a relation is overruled by small variations (as well in time as in place) in the meteorological parameters and maybe also in the emissions, that probably it will be impossible to use a mathematical model for these situations.

Chapter XV

AN AREA SOURCE MODEL WITH STATISTICAL INPUT, ITS VERIFICATION AND ITS VALIDATION; A STANDARD FOR ODOROUS POLLUTION

by

Dr. Louis A. Clarenburg

Rijnmond Authority
Director, Dept. of Environmental Care
The Netherlands

XV-2

RIJNMOND AUTHORITY

C.C.M.S.-meeting, Paris; October 2-4, 1972.

An area source model with statistical input, its verification and its validation; a standard for odorous pollution.

Extended summary by Dr. Louis A. Clarenburg

1. Introduction.

The Rijnmond area is heavily industrialized mainly with refineries and derived chemical industries. It is also a densely populated area with many neighbourhoods, situated in the immediate proximity of these industries. The main air pollution problem is that of odours, leaking into the air by evaporation, breathing of storage tanks, maintenance operations, spillages on the water, etc. Many complaints (about 30,000 in 1971) were received by the control office of the Rijnmond Authority. Statistical analysis of the geographical distribution of these complaints lead to an area source model of odorous pollution, relating perceptive capabilities of the population to production factors, meteorological parameters, and distance (see paragraph 2). Although the model was capable of giving an adequate description of the complaint patterns registered the Rijnmond Authority required a validation of the model along independent ways, before willing to establish an environmental strategy derived from the model.

The model consists of two parts: a diffusion part and a perception part. If the diffusion part was about correct, then it should be capable without modification of predicting the SO_2-pollution levels in cities; this part of the validation is dealt with in paragraph 3. If the perception part was about correct, it should be capable to predict the result of a sociological poll; this part of the validation is dealt with in paragraph 4. After the validation had taken place, the Rijnmond Council established a standard for odorous pollution (paragraph 5), believed to be the first in its kind.

2. Area source model (1).

The model is based on the assumption, that odour emerges from numerous sources, randomly spread over the terrain considered. Moreover, the strengths of all these sources belong to a (non specified) statistical distribution.

By integrating the contribution of a cross-wind row of sources, situated in a band Δx to the concentration at anyone down-wind site, and by subsequent integration in the wind direction, an expression for the total odour concentration is obtained. In its simplest form it reads

$$C(x)_{tot\ i} = \frac{2\,\bar{Q}_i}{\sqrt{\pi}\,\bar{U}\,C_z\,a_i b_i}\left[(X_i + x)^{n_z} - x^{n_z}\right] \qquad (1)$$

where $C(x)_{tot\ i}$ = total odour concentration at distance x from the industrial terrain i,

$\bar{Q}_i/a_i b_i$ = mean source strength per unit of surface area on terrain i,

$\bar{U}$ = mean wind velocity,

.../2

C_z = vertical diffusion parameter,
n_z = vertical stability parameter,
X_i = on-wind dimension of industrial terrain i.

The total concentration is found by summation over all industrial terrains

$$C(x)_{tot} = \sum_i C(x)_{tot\ i} \qquad (2)$$

Odour is a non-defined notion in a complicated agglomeration of (petro)-chemical industries. The composition of the odorous mixture varies from place to place, and at a particular place from time to time. Therefore it is assumed, that this complex mixture of odorous compounds is perceived by the population as if it was one odorous substance with a particular odour characteristic. From laboratory experiments it is known, that the sensitivity to odorous exposure of a group of persons has a log-normal distribution. Integration of this perception distribution between the limits 0 and $C_{tot}(x)$ then gives the fraction of the population f(x), living at distance x from the industrial complexes considered, capable of perceiving the concentration $C_{tot}(x)$.

$$f(x) = G\left(\frac{C_{tot}(x)}{C(x_{th})}\ , \sigma_g\right) \qquad (3)$$

where f(x) is named the penalization function,

$C(x_{th})$ = the threshold concentration, established at distance x_{th} (threshold distance is a function of atmospheric stability),
σ_g = odour characteristic.

As can be seen from equation (3) the production factor $^{Q}/ab$, difficult to estimate, disappears; the potentiality of the industrial complex is contained in its on-wind dimension X.
Using equation (3) a prediction was made of the result of a public poll, held in Geleen. The question to be answered was: Do you perceive nuisance due to air pollution ?
The possibility of response was: yes or no. In figure 1 the situation is depicted. Table 1 shows a comparison between prediction and findings.(See next page).

The complaint patterns in 5 locations in the Rijnmond area were calculated, yielding identical satisfactory results. The impact of the penalization in the down-wind area largely depends on on-wind terrain dimension and on atmospheric stability.

3. Validation of the model; diffusion part (Equation (1)) (2).

Without essential modification equation (1) was used to compute

(a) seasonal mean SO_2 concentrations at various sites in The Hague and Amsterdam;

(b) hourly mean SO_2 concentrations, and their seasonal distribution as a function of wind direction (4 sectors) at the same sites in the same cities.

.../3

figure 1.

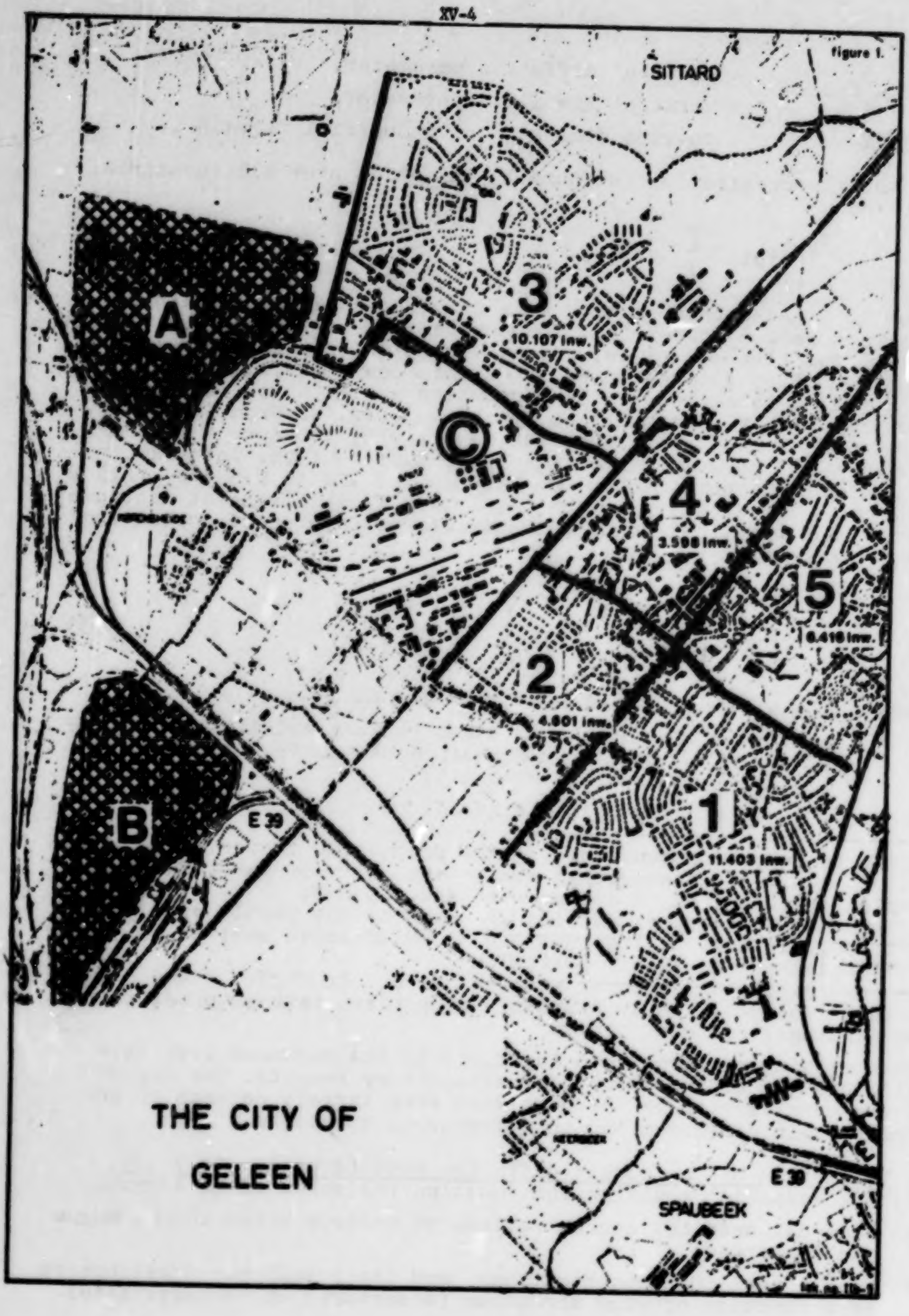

SITTARD
A
3
10.107 inw.
C
4
3.598 inw.
5
6.416 inw.
2
4.801 inw.
1
11.403 inw.
B
E 39
E 39
SPAUBEEK
THE CITY OF
GELEEN

Table 1 - City of Geleen.

Comparison of calculation and public poll.

	Distance relative to complex A in km.	Distance relative to complex B in km.	Distance relative to complex C	f(x) complex A	f(x) complex B	f(x) complex C	f(x) calc.	f(x) + conf. lim. poll
Living quarter								
3	0,1 - 1,5 0,1 - 1,2 g = 3/4	- -	0,25 - 0,6 g = 1/4	0,99 - 0,52 0,99 - 0,60	- -	1,00 - 0,81	0,805	0,83 ± 0,115
2	1,5 - 2,2 g = 3/4	-	0,6 - 0,85 g = 1/4	0,52 - 0,38	-	0,81 - 0,51	0,505	0,51 ± 0,13
5	2,2 - 2,9 2,3 - 3,1 g = 1	- -	- -	0,38 - 0,27 0,37 - 0,24	- -	- -	0,32	0,35 ± 0,10
4	1,7 - 2,4 1,8 - 2,6 2,0 - 3,0 g = 2/3	- - -	0,6 - 0,95 g = 1/3	0,48 - 0,35 0,46 - 0,32 0,41 - 0,26	- - -	0,81 - 0,40	0,415	0,34 ± 0,095
1	2,2 - 3,3 2,3 - 3,5 g = 9/10	1,1 - 1,3 g = 1/10	- -	0,38 - 0,20 0,37 - 0,17	0,37 - 0,32	-	0,27	0,26 ± 0,05
Geleen							0,47	0,475 ± 0,04

.../4

In this case equation (1) is used in absolute sense, hence the value of Q/ab should be estimated for each neighbourhood. From available statistics on fuel consumption both the SO_2-emission per inhabitant and per worker, per season could be determined (inhabitant and worker equivalent respectively). The uncorrected value for Q/ab in each neighbourhood is then

$$\frac{Q}{ab} = \frac{I.E_I + W.E_W}{S} = \bar{L}\,(1 - F) \qquad (4)$$

where I = number of inhabitants in neighbourhood considered,
W = number of workers in neighbourhood considered,
S = surface area of neighbourhood considered,
F = % of non S-containing fuel used in neighbourhood considered,
E_I = inhabitant equivalent per season,
E_W = worker equivalent per season.

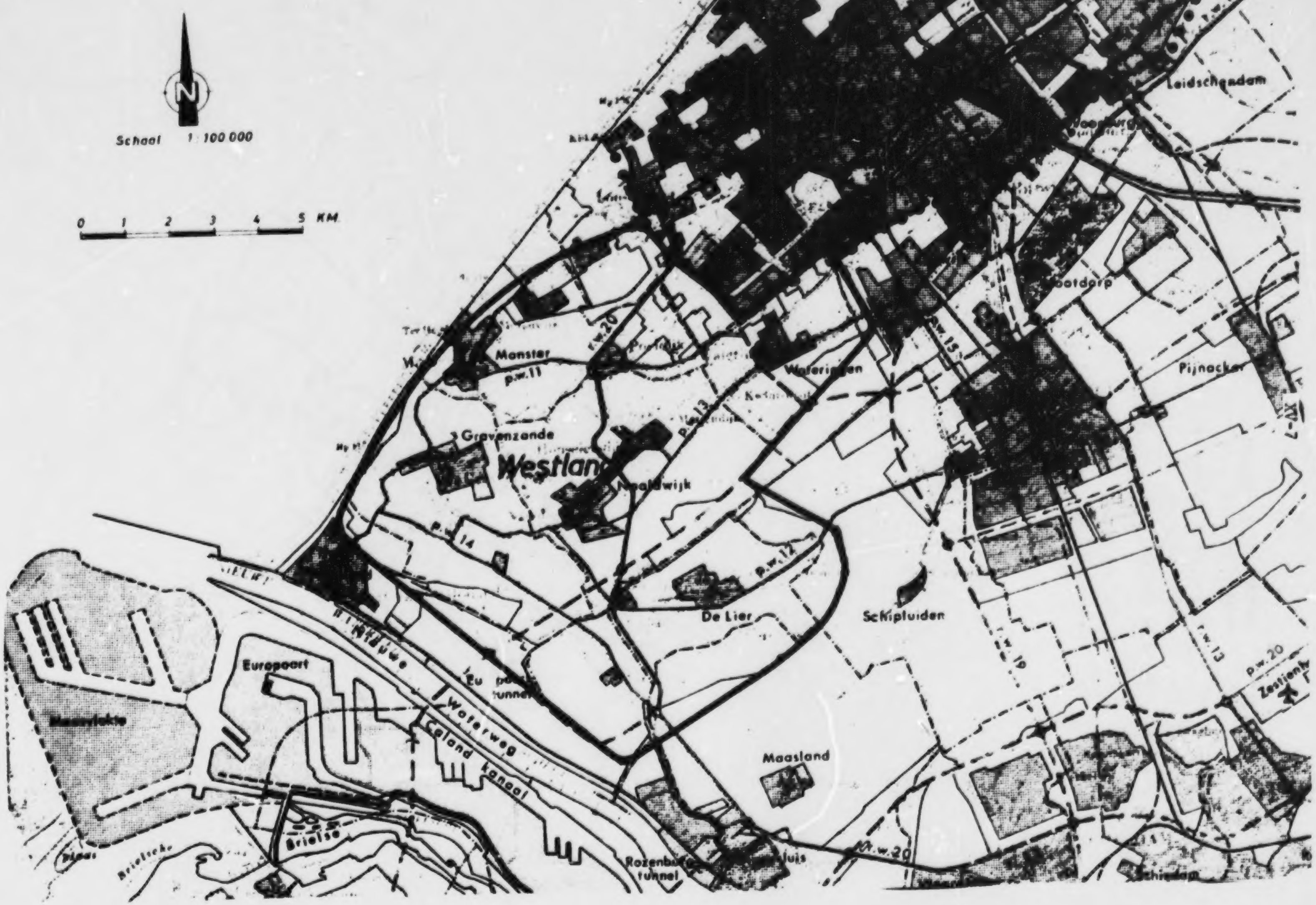
From theoretical considerations concerning heat flux from windows and walls and from draughts through buildings to the atmosphere, it followed that the hourly mean value of $L(L_a)$ is a function of temperature and wind velocity

$$L_a = \bar{L}\left(\frac{T_{in} - T_a}{T_{in} - \bar{T}}\right)\left(\frac{U_a}{\bar{U}}\right)^{\beta}(1 - F) \qquad (5)$$

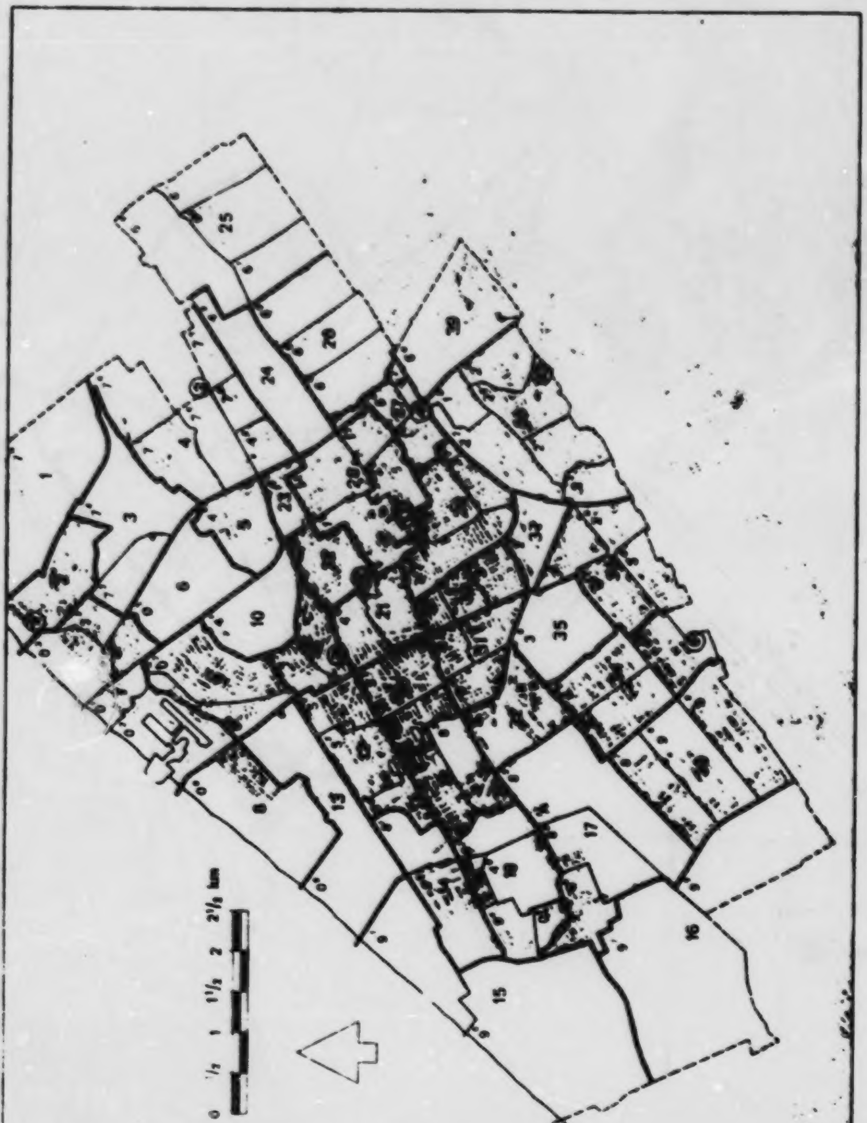
where T_{in} = inside temperature,
T_a = actual outside temperature,
$\bar{T}$ = seasonal mean outside temperature,
U_a = actual wind velocity.

Differences in construction of buildings are responsible for variations in the value of β; its value between the limits 0.6 - 0.8. By substituting (5) in (1), and subsequently using equation (2) the hourly mean concentrations could be calculated in a straight forward way (i.e. without the use of a calibration parameter). The values for C_z and n_z were taken from Gifford and Hanna (3). The required meteorological information (i.e. stability frequences as a function of wind direction, wind velocity) could be obtained from the Royal Meteorological Institute.
All statistics about population density, as well as sampling data could be readily obtained from the municipalities.

As an example one result is reported here. South to South West of The Hague is an important greenhouse area with a low level emission of 180.000 ton SO_2/year (figure 2). At southern wind the contribution to the concentration of SO_2 in the city of The Hague from this area source is super imposed on the contribution from the city sources. The repartition of The Hague in neighbourhoods (figure 3) corresponds with the voting districts. In figure 4 the computed seasonal mean concentrations for all sampling sites are compared with observed data. A comparison of computed and observed distribuigure 2

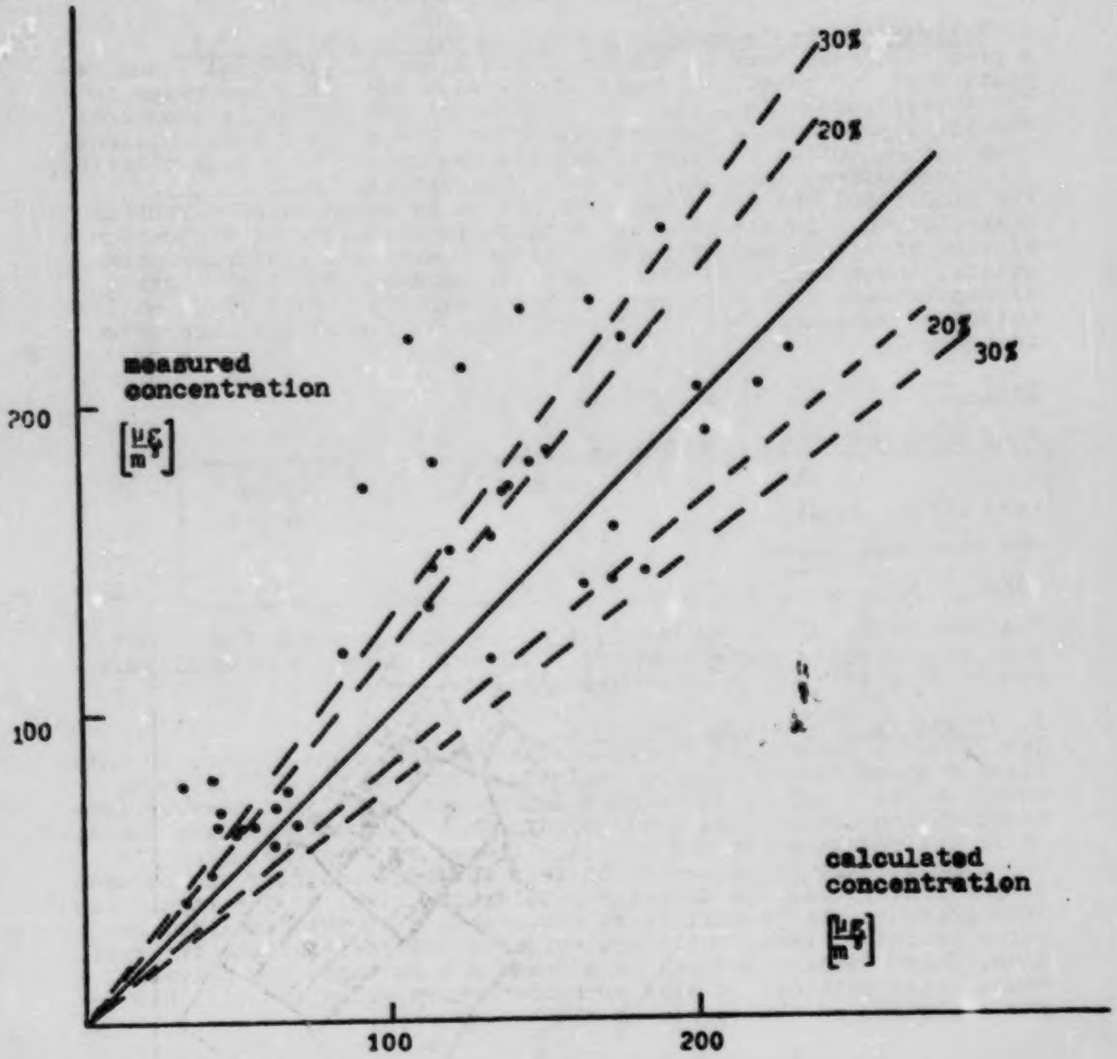

N
Schaal 1 : 100 000
0 1 2 3 4 5 KM
Leidschendam
Voorburg
Ypenburg
Nootdorp
Pijnacker
XV-7
r.w. 40
r.w. 13
r.w. 19
r.w. 20
p.w. 20
Zestienhoven
Wateringen
p.w. 15
Monster
p.w. 11
p.w. 20
Poeldijk
Gravenzande
Westland
Naaldwijk
p.w. 13
p.w. 12
p.w. 14
De Lier
Schipluiden
Maasland
Schiedam
Maassluis
Rozenburg tunnel
Nieuwe Waterweg
Europoort tunnel
Caland kanaal
Europoort
Maasvlakte
Brielse

▬	border of neighbourhood
—	border of ward
30	number of neighbourhood
8	number of ward
- - - -	border of city
③	sampling site


25
20
24
1
3
4
23
22
6
10
21
32
35
39
13
8
14
17
16
15
0 ½ 1 1½ 2 2½ km

city of The Hague

Figure 4



Comparison of the measured and the calculated seasonal mean concentrations in the city of The Hague.

tion of hourly mean concentrations for a down town sampling site is given in figure 5. The correspondence between computed and observed data appeared to be surprisingly close. Total computer time for 10 sites in The Hague (both seasonal mean per wind sector, and distribution of hourly mean values all wind sectors combined) amounted up to 3 minutes, input and output included.

4. Validation of the model, perception part (equation (3)).
A prediction was made of the result of a sociological poll, and deposited at the executive board of the Rijnmond Authority prior to the investigation (4). This poll contained the following question: "Do you experience in the immediate vicinity of your home nuisance from air pollution ?". The answer was restricted to 5 possibilities, i.e. very often, regular, now and then, seldom, never.
For prediction the following data had to be known: wind direction distribution, distribution of atmospheric stability as a function of wind direction and of stability, diffusion and stability parameters, industrial production factors, geographical distribution of population, a good indication how population would react on frequency of exposure. Results for the city of Vlaardingen are shown in table 2.

Table 2 - city of Vlaardingen.

% of the population responding:

	predicted	found
very often, regular	53	56 ± 8
now and then, seldom	45	42 ± 7
never	2	2 ± 2

The results thusfar obtained give an indication about the border line between mere perception and the mental effect nuisance. This can be fruitfully applied in legislation.

5. Standards for odorous pollution (5).
The results, summarized above, enabled the Rijnmond Council to establish a standard for odorous pollution (29th of May 1972). Using equation (2) a map of the Rijnmond area was calculated showing isopenalization lines (figure 6). A reference neighbourhood was taken, where the penalization due to odour seemed to be acceptable. The map showed, that penalization in that reference quarter was between 37 and 32%. Taking the decreasing tolerance level of the population into account, the Council fixed the standard at 30% penalization for a period of time, until new evidence will necessitate for revision. This standard defines land zones not suitable for private house constructions; it also provides a firm guideline till how far abatement at the source should be enforced.

-oOo-

13-10-1972
LC/kl

figure 5

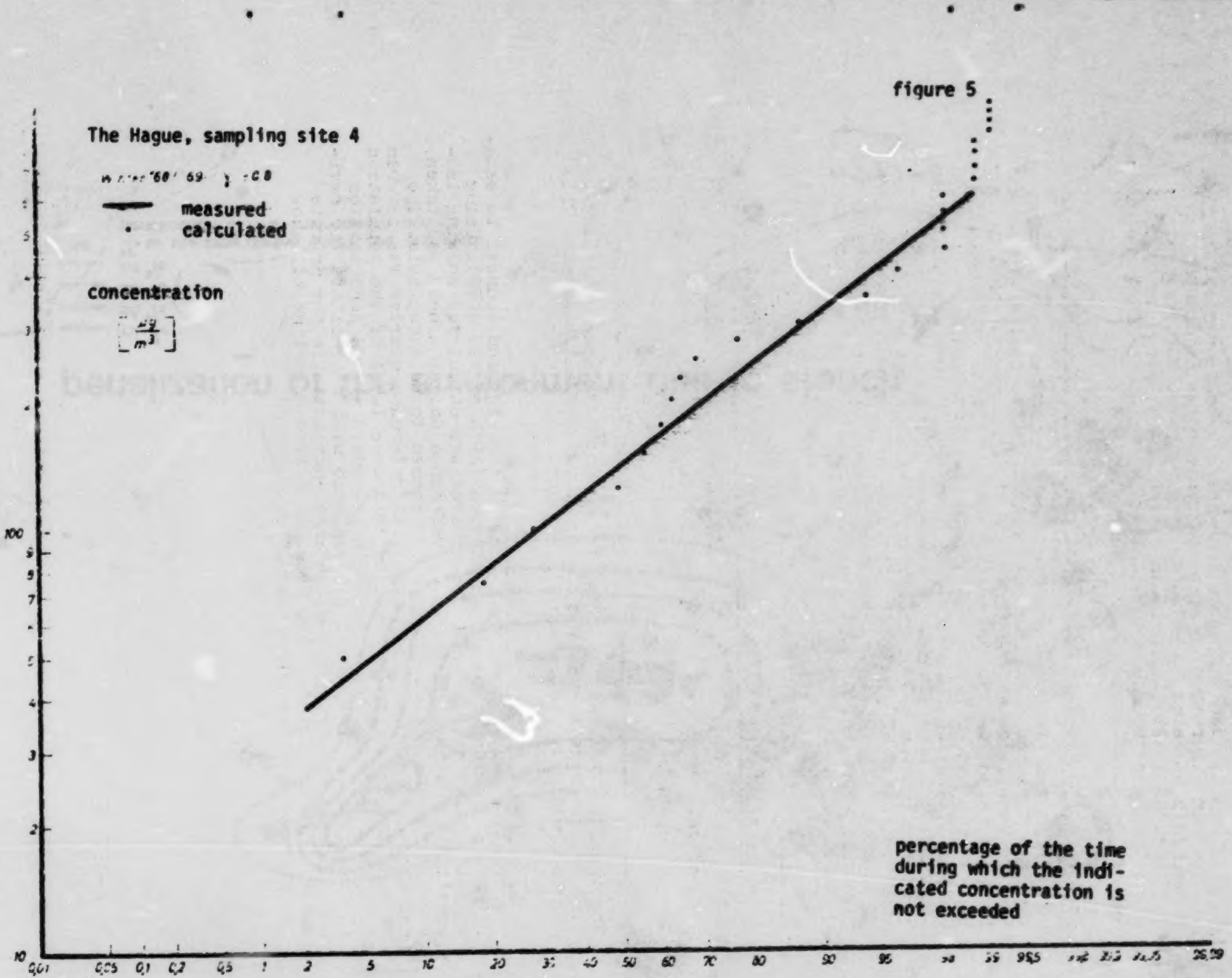
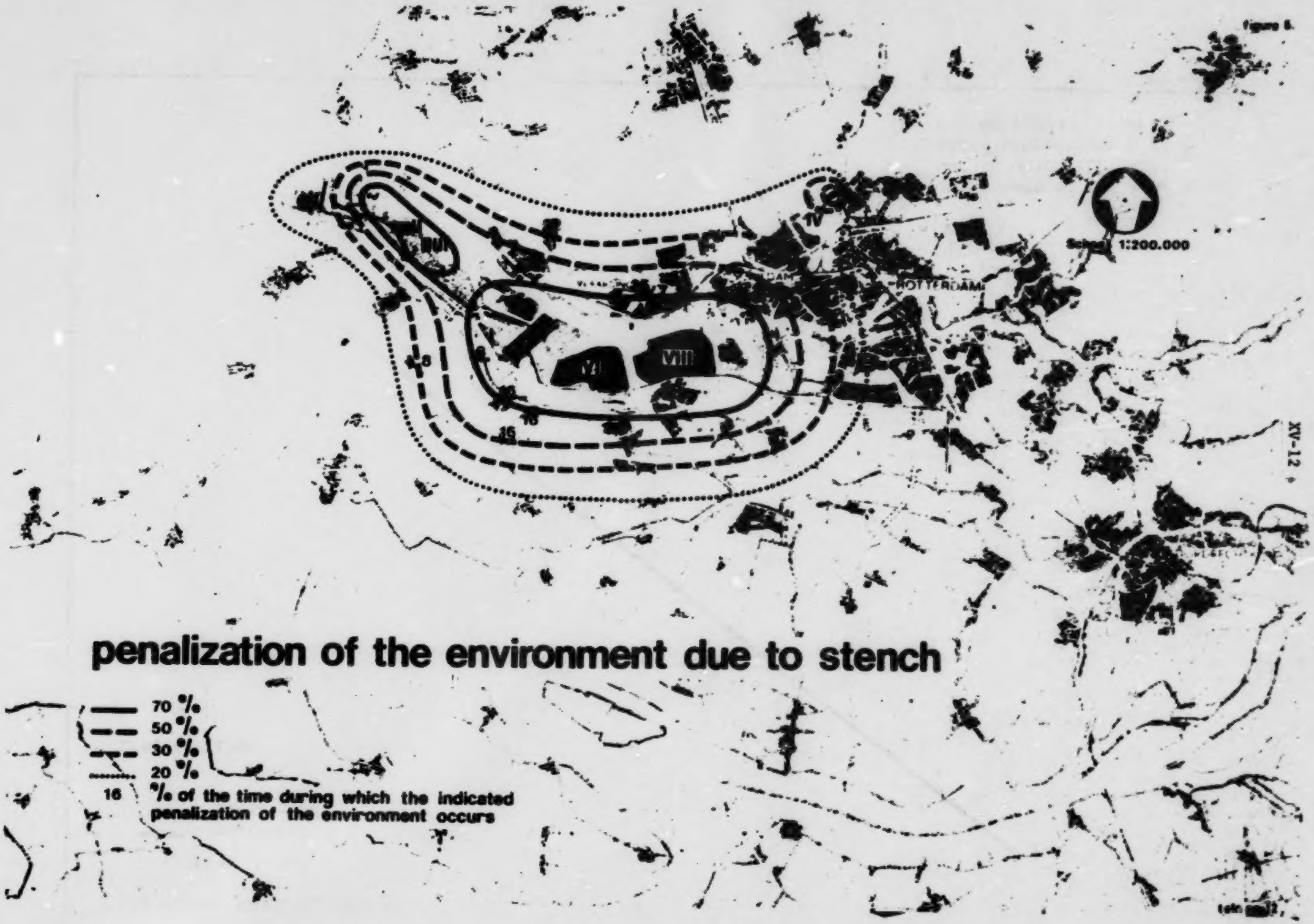

The Hague, sampling site 4
winter '68/'69
measured
calculated
concentration
$\left[\frac{\mu g}{m^3}\right]$
10
2
3
4
5
6
7
8
9
100
2
3
4
5
percentage of the time during which the indicated concentration is not exceeded
0,01
0,05
0,1
0,2
0,5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99,5
99,8
99,9
99,95
99,99

figure 8.



penalization of the environment due to stench

Scale 1:200.000
ROTTERDAM
VII
VIII
16
16
16
70 %
50 %
30 %
20 %
16 % of the time during which the indicated penalization of the environment occurs

REFERENCES:

1. Has been accepted for publication in Atmospheric Environment.
2. Preliminary report available (in Dutch).
   Will be published in 1973.
3. Gifford, F.A. and Hanna, S.R., "Urban air pollution modelling". Proceedings 2nd International Clean Air Congress, p. 1146 (1971).
4. Preliminary report available (in Dutch).
   Will be presented at 3rd International Clean Air Congress (1973).
5. "Milieubelasting door stank", 17 mei 1972; Rijnmond Council 1972/136 nr. 3381 (in Dutch).

Chapter XVI

STATUS OF THE INVESTIGATIONS ON THE EMISSION INVENTORY OF THE DENSELY POPULATED AREA OF LOWER-MAIN (FRANKFURT)

by

W. Lamp

Regionale Planungsgemeinschaft Utermain
Frankfurt, Federal Republic of Germany

Status of the Investigations on the Emission Inventory of the Densely Populated Area of Lowermain (Frankfurt)

W. Lamp

The model, being designed by Prof. Fortak which is supposed for the distribution of sulfur dioxide in the densely populated area of the Lowermain Region requires as input-data the related meteorological data as well as a detailed emission register.

The basic problem of the regional board is to carry out investigations leading to a reasonable emission register.

For this purpose, the emission register has been divided into three main groups:

1. SO_2 - emissions resulting from factories with a capacity of over 800,000 kcal/h which are called point sources. Since these plants mainly belong to the industrial factories, the ascertained emissions were also called industrial emissions with the subdivisions:

   1.1 SO_2 - output of 10 kg/h or more

   1.2 SO_2 - output of 1-9 kg/h or less

2. SO_2 - emissions resulting from furnaces with a capacity of less than 800,000 WE (kcal/h) concerning a SO_2-output of less than 1 kg/h, mainly resulting from housing-areas. They are divided into:

   2.1 SO_2 - emissions of housing areas with a chimney height between 12 and 15 meters.

2.2 SO_2 - emissions resulting from commercial furnaces with a capacity of less than 800,000 WE.

2.3 SO_2 - emissions resulting from furnaces of multi-story-buildings with a capacity of less than 800,000 WE with a chimney height of more than 15 meters.

3. Traffic emissions, which we call line emissions, subdivided into:

3.1 CO - emissions resulting from road traffic

3.2 CO - emissions resulting from inland-water-ways

3.3 CO - emissions resulting from air-traffic

To compile this inventory we had less then $10,000 and two volunteer workers available.

Since the area of investigation covers about 1600 square-kilometers the applied monetary and personnel resources were relatively small, compared with personnel and pecuniary efforts of other German cities, which have made up for an emission register. In spite of these difficulties, we have carried out our investigations in due time.

The Industrial SO_2 - Emission Register

For the industrial SO_2 - emission register questionnaires were used. They got the consent of 18 institutions, in spite of that, they were criticized after they were distributed to the factories. Concerning some questions, we should have given more detailed interpretations.

But the questionnaires would have become much too extensive and quite a number of the managers would have shyed away from answering them. The questionnaire already had 31 questions with several subquestions and some tables that had to be completed.

We distributed more than 800 questionnaires, of which almost 70 percent were filled out and returned. General topics, like locality, height of chimney, co-ordinates, cross-section of the chimney and so on were not answered by about 20 percent, to questions on heating-techniques only 4 percent gave no answer. Some statements were incorrect but could be put right by additional control questions within the questionnaire.

The board of industrial inspection was not able to analyse our questionnaires for lack of personnel. So we asked an engineer to do the analysis for us in his spare time. This man is well versed in industrial heating problems and quite familiar with the industries in our region.

The following pages are copies of analysis-sheets designed to facilitate the task of the analyzer and also to be used for statistical purposes.

We presume that by the end of October 1972 the analysis will have been finished, including completion of those questionnaires that were not fully answered by either telephoning back or investigating personally. We asked the board for industrial inspection to remind the dilatory companies.

The center for data processing in Hessen together with the Meteorological Institute of the Free University in Berlin will continue the interpretation of the data according to the model's regulations.

„FORTRAN"-PROGRAMM

Entwurf v. 22.1.72 wf

Emissionskataster Auswertebogen

für Einzelquellen Stammblatt

Emittenten Nr.	Rechtswert	Hochwert	Brennstoffe*	Schornsteinangaben			Temperatur der Rauchgase an der Schornsteinmündung			Brennstoffmenge bei Vollast		SO_2-Auswurf bei Vollast		Rauchgasmenge bei Vollast		Austrittsgeschwindigkeit der Rauchgase			Brennstoffart	Schwefelgehalt	Anzahl d. Züge	Art der Anlage	[illegible]
				geodät. Höhe	geom. Höhe	oberer lichter Querschn.	Schwachlast	Normallast	Vollast	Mant	E	Mant	E	Mant	E	Schwachlast	Normallast	Vollast					
–	10^{0} m	10^{0} m	–	m	m	10^{-2} m^2	°C	°C	°C	kg/h		kg/h		m^3_nf/h		10^{-1} m/s	10^{-1} m/s	10^{-1} m/s	–	10^{-2}	–	–	–

AUFGABE: * Anzahl der Brennstoffarten

	DATUM	NAME			DATUM	NAME
BEARBEITET:						
GELOCHT:						

DRZ

FOR COMMENT

„FORTRAN"-PROGRAMM

Entwurf v. 22.1.72 Wf

Emissionskataster Auswertebogen

für Einzelquellen Folgeblatt

							3- Stunden- Mittelwerte des Auswurfes in 10^{-1} % der Vollast (0-24 Uhr)							
Emittenten Nr.	Kolonne Nr.	Brennstoffart	Schwefelgehalt	Brennstoffmenge bei Vollast			Montag oder Tag nach Feiertag		Dienstag, Mittwoch, Donnerstag		Freitag oder Tag vor Feiertag		Samstag, Sonntag, Feiertag	
							Winter	Sommer	Winter	Sommer	Winter	Sommer	Winter	Sommer
				Heizöl	L		0 3 6 9 12 15 18 21 3 6 9 12 15 18 21 24	0 3 6 9 12 15 18 21 3 6 9 12 15 18 21 24	0 3 6 9 12 15 18 21 3 6 9 12 15 18 21 24	0 3 6 9 12 15 18 21 3 6 9 12 15 18 21 24	0 3 6 9 12 15 18 21 3 6 9 12 15 18 21 24	0 3 6 9 12 15 18 21 3 6 9 12 15 18 21 24	0 3 6 9 12 15 18 21 3 6 9 12 15 18 21 24	0 3 6 9 12 15 18 21 3 6 9 12 15 18 21 24
–	–	–	10^{-1} %	kg/h										

AUFGABE:		DATUM	NAME	BLATT-NR.	BLATTZAHL
	BEARBEITET:				
	GELOCHT:				

GEPRÜFT:

DATUM	NAME

FOR COMMENT

CONTINUATION

„FORTRAN"-PROGRAMM

Entwurf v. 21.2.72 mf.

STATEMENT NUMMER

Emmissionskataster für Einzelquellen

FORTRAN-STATEMENT

Fragebogen, Statistik

Schlüssel

IDENTIFICATION

Emittenten-Nr.

Name, Telefon
Rechtswert
Hochwert
Höhe Fußpunkt
Höhe Schornstein
Gebäude: Länge
Querschnitt Mdg.
Bauart
Austrittsgeschw.
Austrittstemp. max.
Austrittstemp. min.
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
Art der Anlage
Zahl der Feuerstätten
[illegible]
[illegible]
[illegible]
Tabelle 1
[illegible]
Brennstoffart
Heizwert
Verbrauch max.
Schwefelgehalt m. S
SO_2 - Messung
SO_2 - Gerät
Emissionsschutz
[illegible]
• [illegible]
• [illegible]
• Aschegehalt
Tabelle 2
Jahresverbrauch
Sommerverb.
Winterverb.
CO_2 - Gehalt Mit.
CO_2 - Gehalt Max.
CO_2 - Gehalt Sch.
unterer Heizwert
Aschegehalt

4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

Bearbeiter
Rückfrage [illegible]
Rückfrage [illegible]
Rückfrage [illegible]

nicht beantwortet:

1 kann entfallen
2 geschätzt (bar.)
3 Rückfrage
4
5

beantwortet:

6 gut
7 unklar
8 korrigiert
9
0

AUFGABE:

	DATUM	NAME	BLATT-NR.	BLATTZAHL	GEPRUEFT DATUM	 NAME
BEARBEITET:						
GELOCHT:						

[illegible] BEZUGSANGABEN (STATEMENT-NUMMER)

Emissionskataster, Kontrolle, Einzelquellen Emittenten-Nr.

Fabr. 2.2.72 Vf
872051-33

Bezeichnung	Dimension	Installiert, bzw Angegeben				Vollast			Normallast			Schwachlast		
					Summe			Summe			Summe			Summe
Brennstoff	–													
Dampfleistung	t/h													
Enth. - Differenz 535	kcal/kg													
Nutzwärmeleistung	Gcal/h													
Wirkungsgrad	%													
Brennstoffwärme	Gcal/h													
Heizwert H_u	kcal/kg (m^3)													
Brennstoffmenge	(m^3) kg/h													
CO_2 ; n	% ; –	/	/	/	/	/	/	/	/	/	/	/	/	/
Schwefelgehalt im Brennst.	Gew.-%													
SO_2 - Auswurf	kg/h													
spezifische Abgasmenge	m^3_{nf}/kg (m^3)													
Abgasmenge	m^3_{nf}/h													
Abgastemperatur Eintr. Sch.	°C													
Abgastemp. - Verlust	grd													
Abgastemperatur Mündung	°C													
" "	°K													
Abgasmenge	m^3/h													
"	m^3/sek													
Mündungsquerschnitt	m^2													
Austrittsgeschwindigkeit	m/sek													
Winter Brennstoffmenge	t (m^3)													
5088 h	(m^3) kg/h													
Brennstoffwärme	Gcal/h													
" bez. auf Vollast	%													
" bez. auf Summe	%													
Sommer Brennstoffmenge	t (m^3)													
3672 h	(m^3) kg/h													
Brennstoffwärme	Gcal/h													
" bez. auf Vollast	%													
" bez. auf Summe	%													

SO_2 - Emission Inventory for Residential Combustion

To create this register it was decided that the best way was to determine the required heat per hour per unit-square each for solid, liquid and gaseous fluid separately, and then, using the grade-day-number, calculate the SO_2 amount by way of the stoichiometrical equations.

As a unit of a densely populated area we decided on 25 hectar (appr. 62.75 acres), that is 500 m by 500 m. If we had used larger areas as a unit the emission-sources of a stronger or a more concentrated kind would have been camouflaged, and when extrapolation is used false or inaccurate emission-values would result.

We have finished the inquiry on heat-demand in the almost 2100 units, situated in our research-region. Industrial business and higher buildings with chimneys of a height of more than 15 m (point-sources) having furnaces of less than 800,000 heat-units are to be registered separately. These two groups together form about 10 to 15 percent of the emission-register for residential combustion.

An inquiry-form was utilized (see following page) and the corresponding data entered.

The data processing-center in Hessen will calculate the maximum output of SO_2 per area and the maximum output of SO_2 per area resulting from the grade-day-number during the heating-period of 1970/71.

The results of this calculation will also be forwarded to the Meteorological Institute of the Free University in Berlin, where the data will be used for the expansion-model.

Traffic - Emission Inventory

This will probably present our greatest problem. The following institutions are cooperating:

the Meteorological Institute of the University Frankfurt

the department for traffic-planning in Frankfurt

the board for road-building in Hessen as far as personnel allows

the center of data processing in Hessen

the Meteorological Institute of the Free University in Berlin

consulting functions:

Prof. May, Kaiserslautern

TÜV, Cologne (department for routine car testing)

As far as I know, here in the German Federal Republic nothing has yet been published on the methodology for setting up a traffic-emission-register. We therefore relied on American publications.

Emissions must be determined by considering the average speed of the cars and the number of kilometers driven by all vehicles in the area or in parts of it (for instance in Frankfurt). The average speed is determined by driving along in the flow of traffic. As a meter, a normal line recorder is recommended, which has to be built into the car doing the measuring. The time for measuring should either be from 6 a.m. to 8 p.m. or during the rush hours as well as during the other hours.

Emissions of a vehicle at certain speeds can be measured on the test bed. The TÜV in Cologne has the data, which the staff of the regional planning-association Lowermain, will have at its disposal by October 1972.

Emissionskataster „FORTRAN-PROG... Stand: 1.7.1972

Hausbrand - Flächenquellen FORTRAN-STATEMENT **Erhebungsbogen**

Karten-art	Schlüssel-nummer der Gemeinde	Lage der Fläche		mittlere geodät. Höhe d. Fläche	mittl. geometr. Höhe d. Quellen	maximaler Wärmebedarf pro Stunde für Brennstoff		
		Rechts-wert	Hoch-wert			fest	flüssig	gasförmig
—	—	10^1 m	10^1 m	m	m	10^3 kcal/h	10^3 kcal/h	10^3 kcal/h

a) Die Lage d. Fläche ($500\,m \times 500\,m = 25$ ha einer Siedlungsfläche) ist gekennzeichnet durch ihren südwestlichen Eckpunkt im Gauß-Krüger-Koordinatennetz

	DATUM	NAME
BEARBEITET		
GELOCHT		

By using these emission-factors, the traffic count and the average speed, we can derive the line-emissions. They result from multiplying the CO-content with the number of kilometers driven by the cars at a certain average speed.

With the assistance of the Federal Board for Transport the following data are also desirable:

type of vehicle (the average distribution of the different types of cars in the Federal Republic is known and should be valid also for the region Lowermain)

the car's year of production

cars with automatic transmission

cars with standard transmission

cars with a gas burning engine

cars with a Diesel-engine

We plan to register the CO-amount on days as follows:

working days (Monday through Friday)

weekends

Sundays and holidays

times of vacation

and times as follows:

6 a.m. to 10 a.m.

10 a.m. to 4 p.m.

4 p.m. to 10 p.m.

10 p.m. to 6 a.m.

This covers the daily routine. Measuring should be made at 4 or 5 representative places.

The Meteorological Institute of Berlin had asked to measure the traffic-emission in each street, but this can hardly be done for technical reasons as well as for lack of personnel. We plan to consider these emissions as forming one percent of the entire emission amount.

For the traffic count more than 300 intersections are at the disposal of the department for traffic planning in Frankfurt (according to a count in 1962). Therefore traffic emissions cannot only be applied as line sources but also as area sources. This latter method will allow us to include the emissions of the neighboring streets.

The chart showing the traffic density gives only material on workday traffic and is based on 25 places in the region's test area outside of Frankfurt, where continuous traffic count has been installed. They are conveniently located in the South and East of the test area, less so in the West and North.

In addition Frankfurt has a few big and a number of temporary places for traffic count, that can be put to work when required.

In areas where we have no data for Sunday traffic, it can be judged by extrapolation based on workday traffic.

The kilometers driven by all vehicles can be ascertained from the traffic density. By using the emission factors we can calculate the intensity of the line sources and also, when applying a grid-system, the intensity of area sources of the traffic. To get a complete picture of the traffic emissions we must also define the average speed, or rather the average speed-cycle within the test area. The latter is more precise, it is defined by test rides in control cars with a built-in ride recorder.

Should all work on the traffic-emission-register operate on schedule, all statistical material will be accumulated by the end of 1972 and analysis will be completed according to plan next year.

For the time being we count on

1. the driven kilometers in Frankfurt being defined by the end of July 1972,
2. the traffic density with the day-routine definition being known by the end of November 1972,
3. receiving in the near future the data on the vehicles, the data from the Europe-cycle, and the data on the average speed.

For the CO-diffusion-model the following facts also have to be taken into consideration:

width of the streets

the streets' position to the main wind direction

height of the bordering houses

CO-distribution at the upper edge of the houses, probably to be learned from corresponding publications.

The Meteorological Institute of the University of Frankfurt is going to measure CO-emissions near big intersections with traffic count, to compare them with the emissions measured there.

Emissions of air-traffic are likely to be of minor importance compared to other traffic emissions. This results from publications by experts on various big international airports outside of the Federal Republic.

Nevertheless we want to try to define the airplane emission above the landing and take-off approach lanes of the Frankfurt airport, and we will work together with the Lufthansa, air-traffic safety control and Boeing in Seattle.

Chapter XVII

A Scheme for Estimating the Vertical Dispersion of a Plume from a Source Near Ground Level

by

F. B. Smith
United Kingdom

Introduction

The new scheme outlined here brings up to date and enlarges upon an earlier scheme by Pasquill (1961) developed to estimate vertical spread of a neutral plume downwind from a near groun-level source when preferred direct measurements of the vertical fluctuations of the wind are unobtainable.

The scheme has utilized numerical solutions of the diffusion equation up to 100 km downwind with profiles of wind, u (z), and diffusivity, K (z), suggested by actual measurements in unstable, neutral and stable conditions. Further measurements of long-range diffusion and a rather better understanding of the nature of the whole boundary layer have both contributed to the changes.

The subject is a very complex one and no simple scheme can really hope to be acceptably adequate on every occasion. Nevertheless, the scheme attempts to take into account the effects of time of day, month, surface roughness, wind speed, incoming solar radiation and overall stability. Other factors, possibly important, have yet to be considered; two of which are:

(i) the effect of significant topographical features (such as drainage into a valley), and

(ii) thermals carrying parts of the plume up to cloud level.

Beyond these, the accuracy of this, or any other, scheme is strictly limited by considerable variations in σ_z from one time to the next in ostensibly the same conditions of wind speed, stability, etc., due to the inherently patchy nature of turbulence in the atmosphere.

An Outline of the Procedure

Two stabilities are important in medium or long-range travel:

(i) The stability of the atmosphere's lower layers, first designated in Pasquill's original scheme as a measure of the rate of vertical diffusion resulting from both mechanical mixing and the supplementary (or repressive) influences of buoyancy arising from the flux of sensible heat.

This stability was classified by defined categories A to F (G added later), A being the most unstable situation associated with large heat fluxes and light winds, D being the neutral situation with small heat fluxes and fairly strong winds, and F being a very stable situation associated with night time clear skies and very light surface winds.

For convenience numerical values P, from 0 to 7, are associated with these seven categories, so that for example P = 2.2 is towards the more unstable end of category C. The second stability is:

(ii) The overall stability of the boundary layer as a whole, as revealed by the temperature profile and the gradient wind. Sometimes these two stabilities are very much in the same sense, but not always. For example, on a summer morning with clear skies and light winds, stability (i) might correspond to P = 1.5 (i.e., unstable) whereas stability (ii) would probably correspond to a stable anticyclonic subsiding boundary layer with the remnent of a marked nocturnal, plus synoptic, inversion being eroded from below by the turbulent mixing layer implied by stability (i).

The existence of two stabilities is not a contradiction but a reminder that vertical spread may initially be determined by P, but at greater distances by the overall stability (ii).

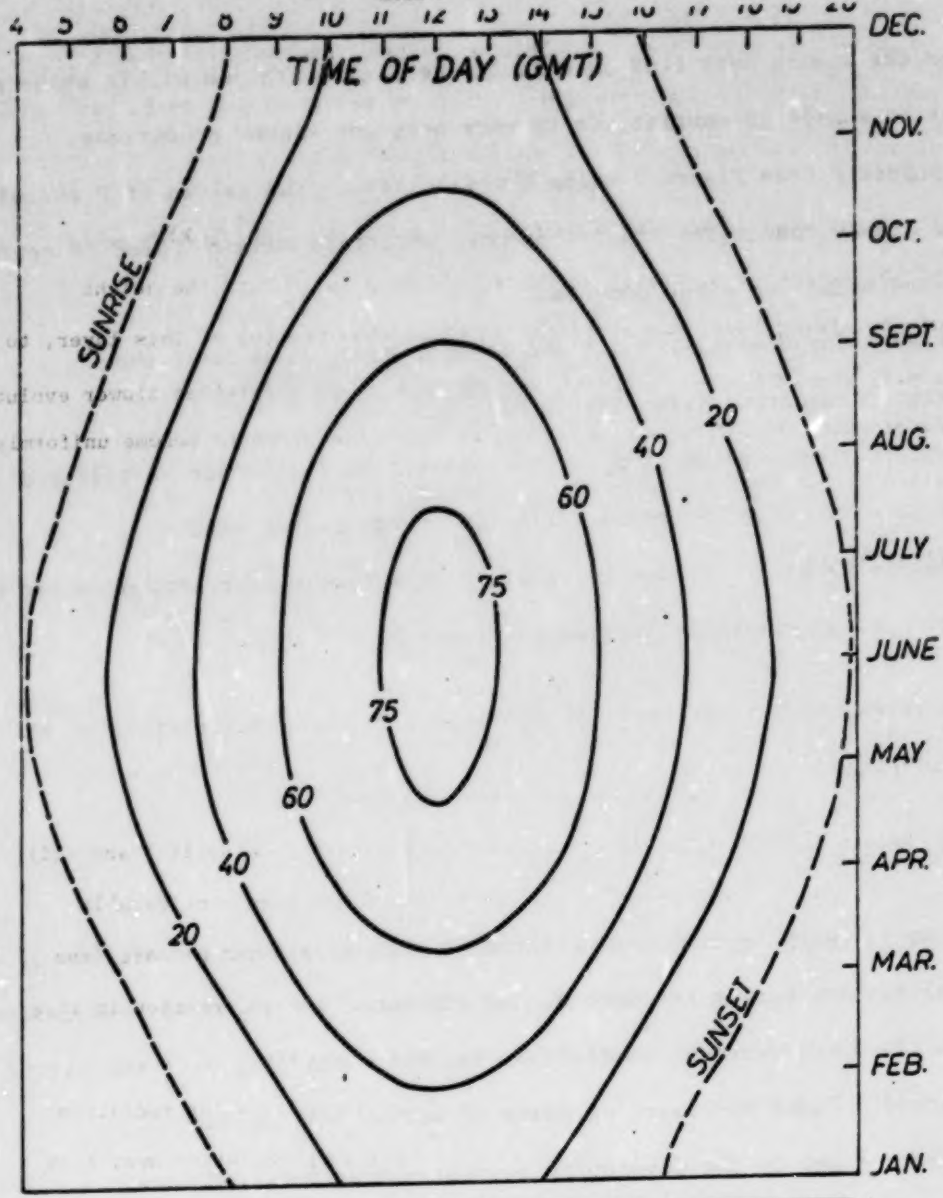
The first step is to determine P and to use it to find $\sigma_z(X)$ in terms of the surface roughness z_0. The second step is to find the height of the mixing layer and after the plume reaches the top of this layer, to modify the further development of $\sigma_z(X)$ to the rather slower evolutionary development of the mixing layer and to allow the plume to become uniformly mixed within it.

First Stage

1. Determine (i) the cloud amount
   (ii) time of day and month
   (iii) wind speed at 10 metres
   (iv) typical roughness over track

2. Deduce the incoming solar radiation from Figure 1 using 1(i) and (ii), or by direct measurement. The effect of cloud has been considerably simplified and, if required, more involved allowances can be made (see for example Smithsonian Meteorological Tables). The information in this figure comes from analysis of Cambridge radiation data.

3. Deduce the sensible heat flux H. From the incoming solar radiation an allowance of about 10 mw/cm^2 net black-body long radiation away from the surface is made, and of the remainder (if any) 40% is assumed (on average) to go into the sensible heat flux H, i.e., $H = 0.4\ (R-10)$ mw/cm^2.



Incoming Solar Radiation
(mw/cm^2)
at Cambridge
(0-1 eighth cloud)

Cloud amount	Multiply I.S.R. by:
0	1·07
1	0·89
2	0·81
3	0·76
4	0·72
5	0·67
6	0·59
7	0·45
8	0·23

Figure 1. The incoming solar radiation in milliwatts per cm^2 reaching the ground on a cloudless day is expressed in the main figure in terms of time of day & month. For cloudy conditions multiply this amount by the factor appropriate to the cloud amount in eighths.

Thus the upward heat flux is normally very close to you within about an hour of sunset or sunrise, or in very overcast winter conditions.

4. Deduce P from Figure 2 using H and 1 (iii). The values of P for night time stable conditions are rather more uncertain and are based on estimates of wind speed and cloud amounts.

5. Read σ_z for neutral $P = 3.6$ and a supposed $z_c = 10$ cm at the distance χ required, using Figure 3.

6. Multiply this value of σ_z by the correction factor for stability given in Figure 4. Note the small variation in the factor with χ.

7. Multiply this corrected value of σ_z by a further correction factor for terrain roughness (1(iv)) given in Figure 5.

This gives the best estimate of σ_z subject to the modifications of the second stage.

Second Stage

Figures 6-8 give typical mixing depth heights as a function of time of day for midsummer, spring and autumn, and midwinter for clear sky conditions, 4/8th cloud and overcast conditions, assumed unchanging over the period concerned. These are based on means of actual Balthum ascents at Cardington* and on the developing boundary-layer model of Carson (1972). Also shown are the corresponding time variations of the P-stability, and

---

*These ascents have been extensively analyzed by R. Hardy (Met. Office) who has kindly allowed his meaned profiles to be used here.

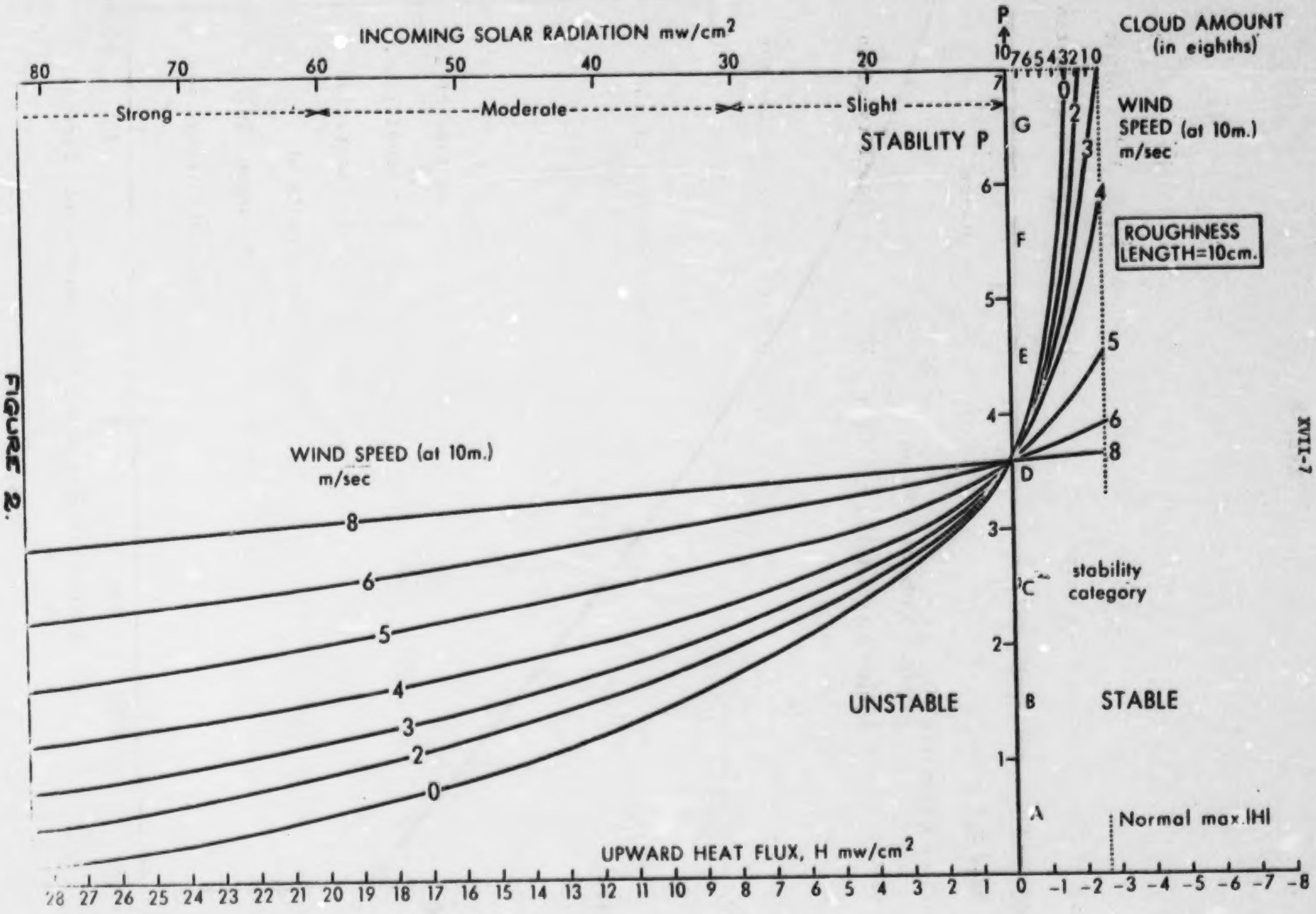

INCOMING SOLAR RADIATION mw/cm²
80
70
60
50
40
30
20
10
Strong
Moderate
Slight
STABILITY P
P
7
6
5
4
3
2
1
G
F
E
D
C
B
A
stability category
CLOUD AMOUNT (in eighths)
7 6 5 4 3 2 1 0
WIND SPEED (at 10m.) m/sec
0
2
3
4
5
6
8
ROUGHNESS LENGTH=10cm.
WIND SPEED (at 10m.) m/sec
8
6
5
4
3
2
0
UNSTABLE
STABLE
Normal max.|H|
UPWARD HEAT FLUX, H mw/cm²
28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8

FIGURE 2.

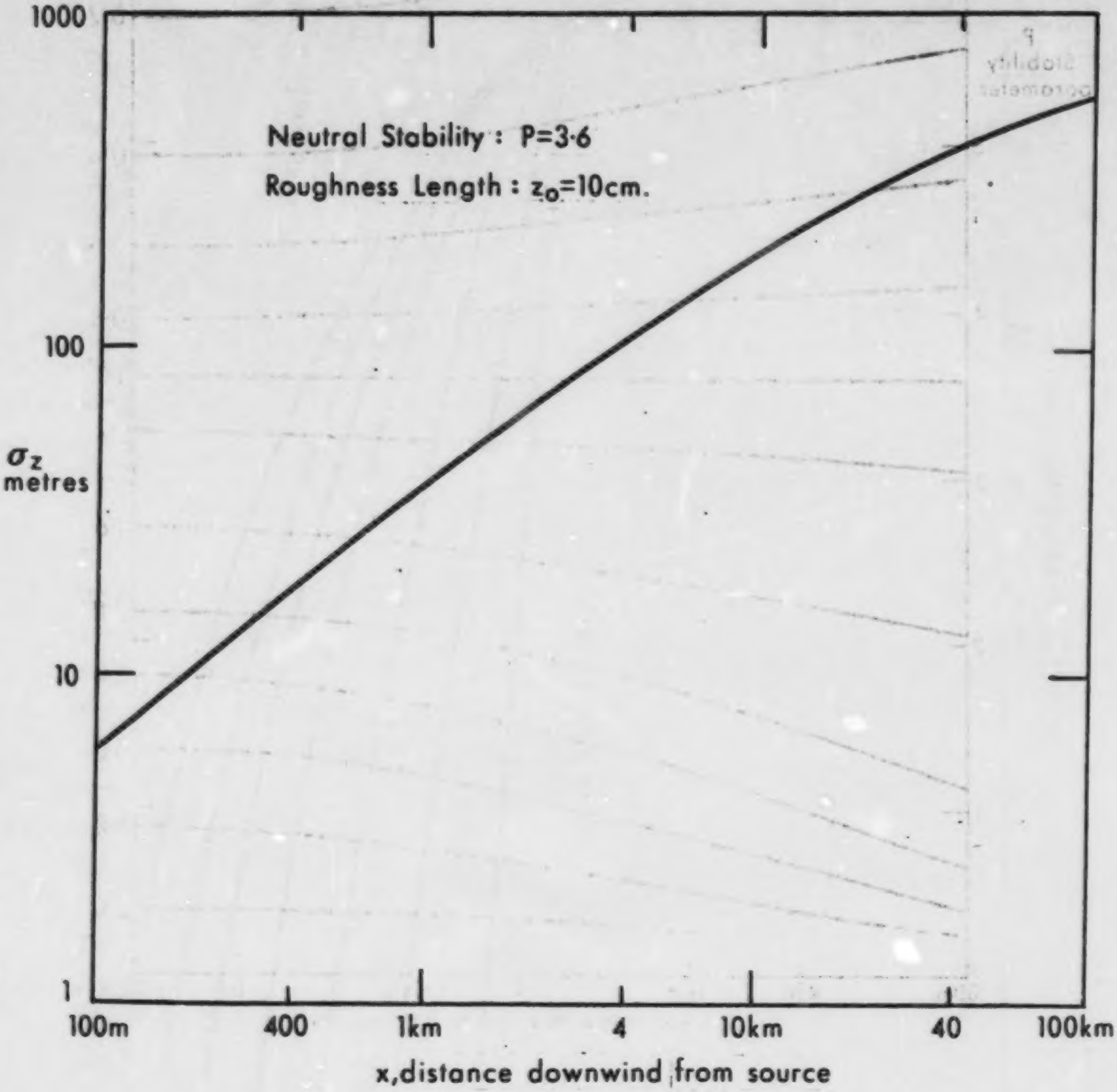

Neutral Stability : P=3·6
Roughness Length : z_o=10cm.
1000
100
10
1
σ_z metres
100m
400
1km
4
10km
40
100km
x, distance downwind from source

FIGURE 3.

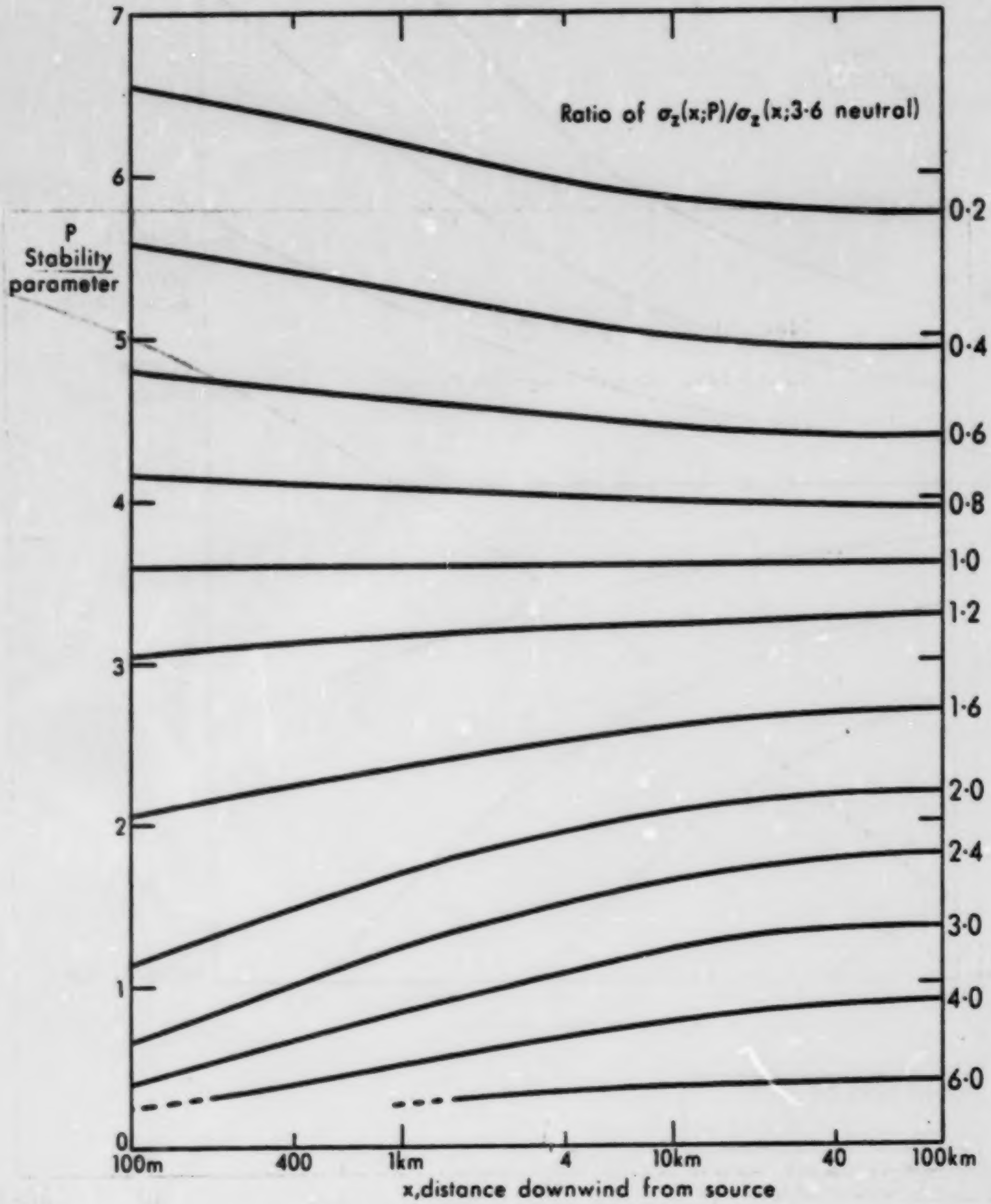
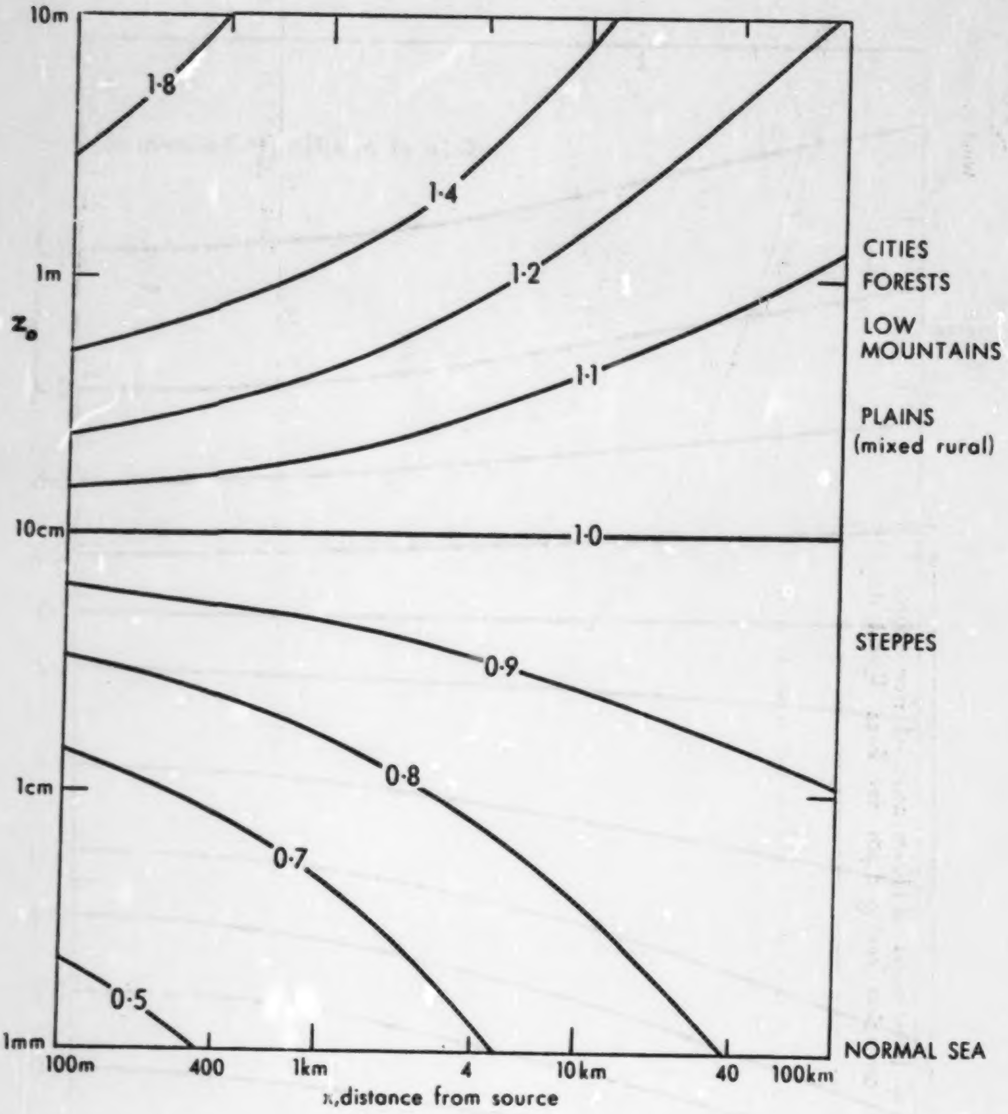

Ratio of $\sigma_z(x;P)/\sigma_z(x;3\cdot6 \text{ neutral})$
P
Stability parameter
7
6
5
4
3
2
1
0
0·2
0·4
0·6
0·8
1·0
1·2
1·6
2·0
2·4
3·0
4·0
6·0
100m
400
1km
4
10km
40
100km
x, distance downwind from source

FIGURE 4.



CONTOURS OF
$\sigma_z(x;z_0)/\sigma_z(x;z_0=0{\cdot}1\text{m})$

These curves are virtually independent of heat flux

FIGURE 5.

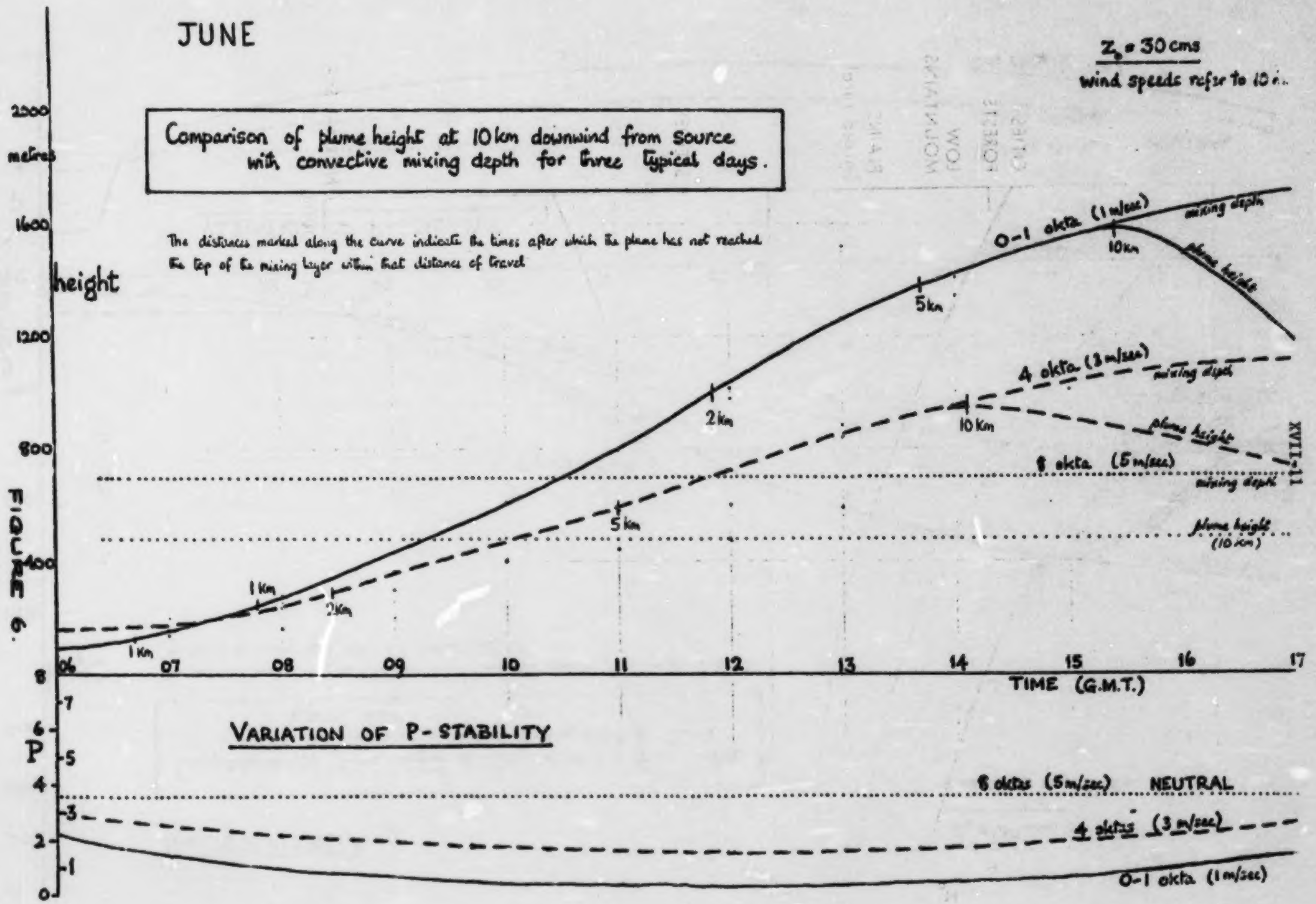
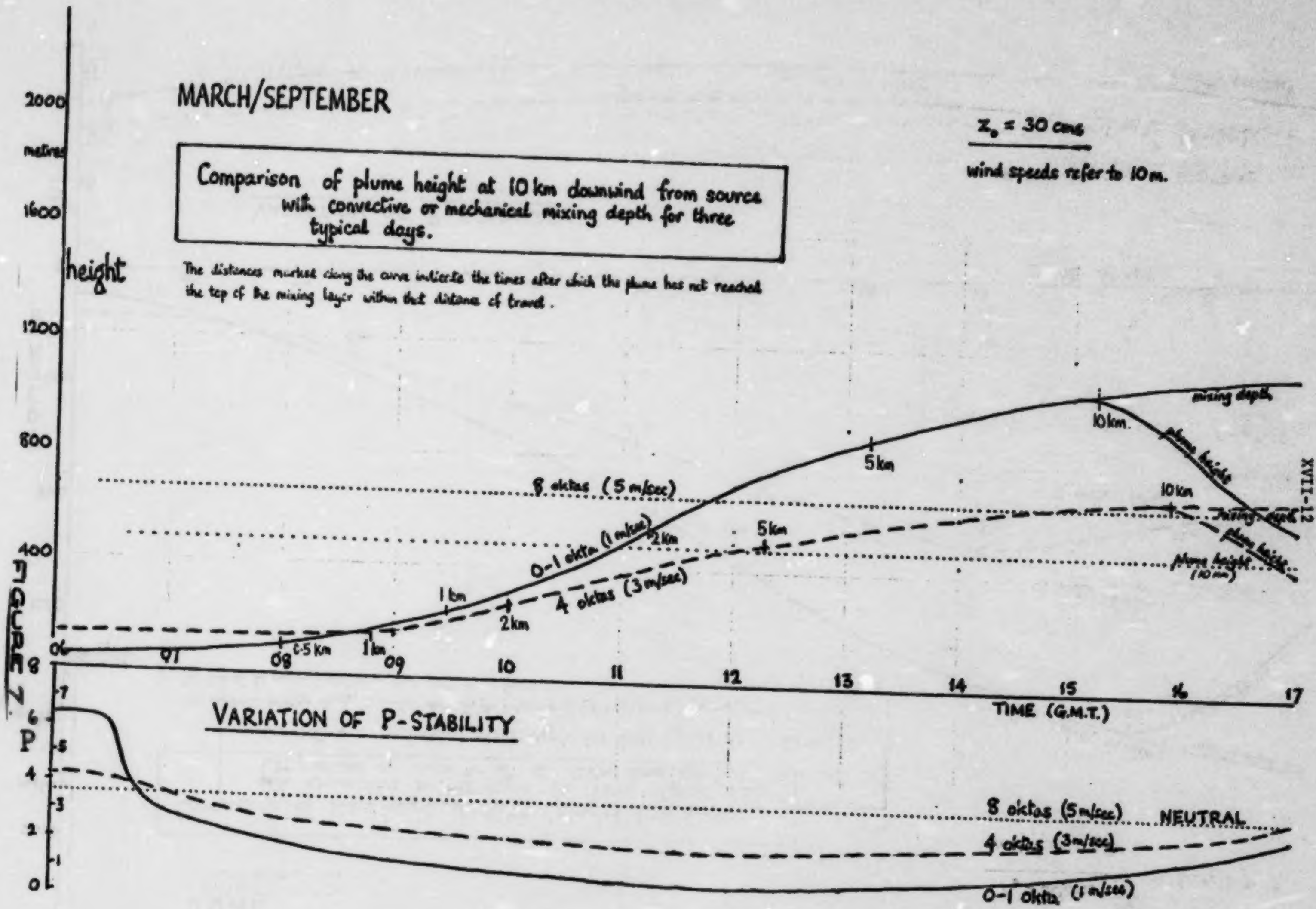

JUNE
Comparison of plume height at 10 km downwind from source with convective mixing depth for three typical days.
$Z_0 = 30$ cms
wind speeds refer to 10 m
The distances marked along the curve indicate the times after which the plume has not reached the top of the mixing layer within that distance of travel
height
metres
2000
1600
1200
800
400
06
07
08
09
10
11
12
13
14
15
16
17
TIME (G.M.T.)
0-1 okta (1 m/sec)
mixing depth
plume height
10 km
5 km
2 km
1 km
4 okta (3 m/sec)
mixing depth
plume height
10 Km
5 km
2 Km
1 Km
8 okta (5 m/sec)
mixing depth
plume height (10 km)
VARIATION OF P-STABILITY
P
8
6
4
2
0
7
5
3
1
8 oktas (5 m/sec) NEUTRAL
4 oktas (3 m/sec)
0-1 okta (1 m/sec)

FIGURE 6.



MARCH/SEPTEMBER

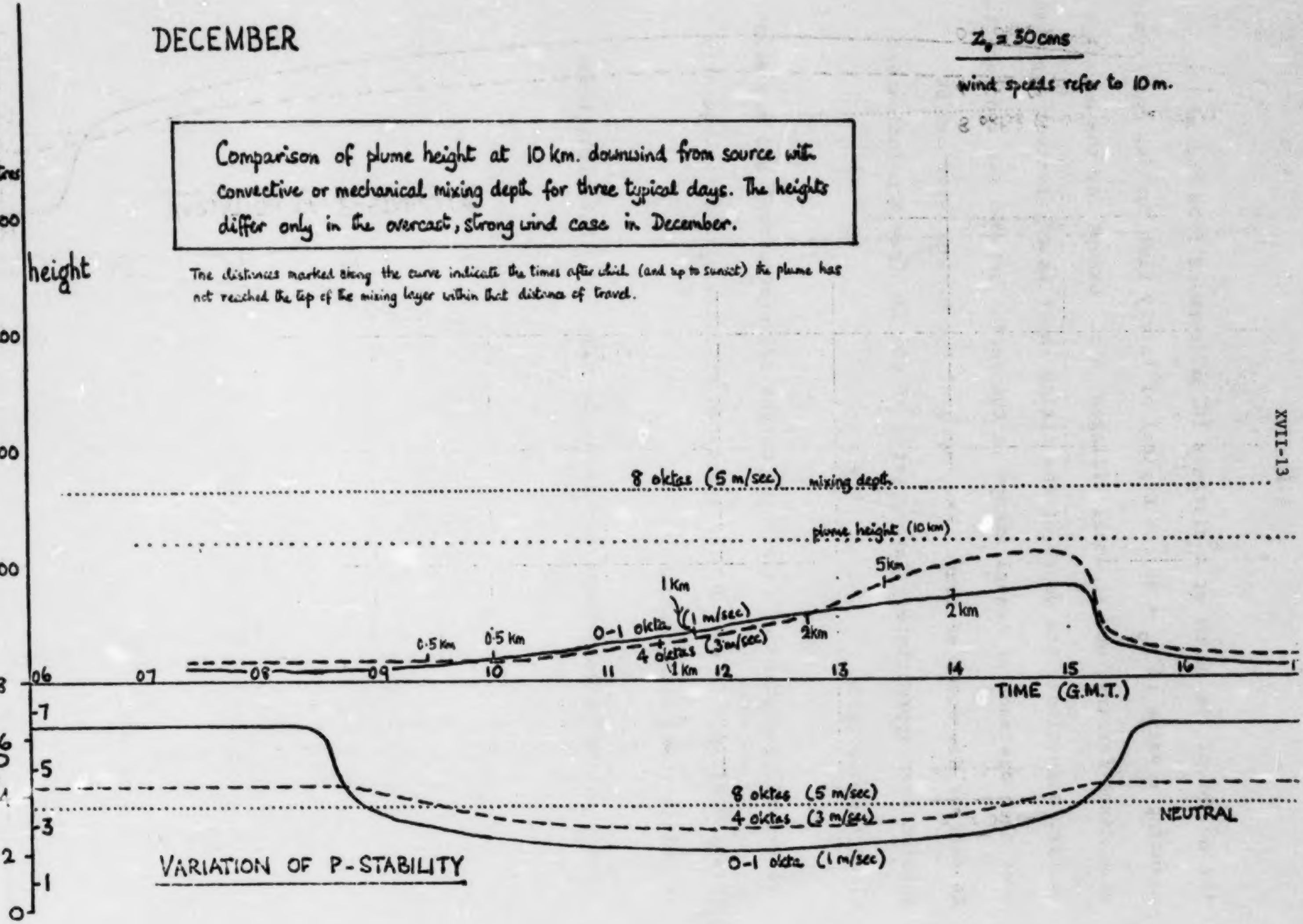
Comparison of plume height at 10 km downwind from source with convective or mechanical mixing depth for three typical days.

z_0 = 30 cms

wind speeds refer to 10 m.

The distances marked along the curve indicate the times after which the plume has not reached the top of the mixing layer within that distance of travel.

FIGURE 7



DECEMBER

$Z_0 = 30$ cms

wind speeds refer to 10 m.

Comparison of plume height at 10 km. downwind from source with convective or mechanical mixing depth for three typical days. The heights differ only in the overcast, strong wind case in December.

The distances marked along the curve indicate the times after which (and up to sunset) the plume has not reached the top of the mixing layer within that distance of travel.

metres
1600
height
1200
800
400
8
8 oktas (5 m/sec) mixing depth
plume height (10 km)
5km
1 Km
2km
0·5 Km
0·5 Km
0-1 okta
(1 m/sec)
4 oktas
(3 m/sec)
2km
1 Km
06
07
08
09
10
11
12
13
14
15
16
TIME (G.M.T.)
7
6
5
4
3
2
1
0
P
8 oktas (5 m/sec)
4 oktas (3 m/sec)
0-1 okta (1 m/sec)
NEUTRAL
VARIATION OF P-STABILITY

FIGURE 8.

the height of the plume at a distance 10 km downwind from the source assuming a value of z_o = 30 cms typical of fairly flat English countryside with mixed farming, woods, small villages, etc. Except for the overcast neutral situations, the depth of the mixing layer is of greatest importance over this distance of travel except in the period between 14Z and sunset. At shorter distances of travel the depth of the mixing layer can be ignored over appropriately larger parts of the day (see the indicators along the curves).

It should be emphasized that these curves are provisional and represent mean conditions in steady wind and cloud situations, and consequently should be used with caution.

Interpolation between these curves may be made for other situations.

Chapter XVIII

THE PREDICTION OF HIGH CONCENTRATIONS OF SULPHUR DIOXIDE IN LONDON AND MANCHESTER AIR

by

F. B. Smith and G. H. Jeffrey, Met 0 14

XVIII-2

The Prediction of High Concentrations of Sulphur Dioxide in London and Manchester Air

By F.B. Smith and G.H. Jeffrey, Met O 14

An Extended Summary

Daily average concentrations of sulphur dioxide in Inner London and in Manchester have been examined in detail for two winter periods, October 1968 - March 1969 (incl.), and October 1969 - March 1970 (incl.). The data have come from the Warren Spring Laboratory (DTI) National Survey Network sites and attempts are made here to explain the concentrations in terms of the prevailing meteorological situations day-by-day. Three forecasting schemes have been developed; the first provides a means of forecasting on any particular day whether or not certain threshold concentrations will be exceeded. The second sets out to forecast as well as possible the actual magnitude of the daily-average concentration, while the last scheme presents a very practical and simple, albeit a slightly less accurate, version of the second scheme. The last scheme is likely to become operational at the London Weather Centre later in 1972.

Overall the schemes show very satisfactory measures of success in both cities and are much superior to using a persistence forecast, i.e., today's concentration estimate is yesterday's concentration.

The meteorological parameters that are most relevant are briefly:

(a) the minimum temperature which affects both the source output and the stability of the lower layers of the atmosphere.

(b) the wind speed. Wind speed enters in two ways, it affects the initial dilution and ventilation at the source and it affects the

stability of the air and the subsequent vertical spreading. In the scheme the number of hours t_{calm}, when the mean wind is less than 3 knots (or in the simplified scheme less than 5 knots) is one important parameter. The mean wind for the day is also of some importance in that when it is small the previous day's emission may still be partially present and significantly affect the current concentrations.

(c) wind direction can be important whenever the geographical distribution of sources is significantly non-homogeneous. Some such influence is noted for London but is negligible in Manchester as a whole.

(d) mixing depth. For limited urban areas the atmospheric mixing depth will only significantly affect mean surface concentrations when it is low for a large part of the day. Two criteria are specified, either of which will lead to higher concentrations:

(i) day: lowest inversion, or cloud base, below 500m following night: surface inversion sets in before 18Z because the 10m wind $V \leqslant$ 8kts and cloud $\leqslant$5/8ths.

(ii) day: lowest inversion, or cloud base, below 300m following night: surface inversion sets in before 21Z because $V \leqslant$ 8kts and cloud $\leqslant$7/8ths.

The Threshold Scheme

The threshold scheme (Part I) aims to forecast whether or not the mean concentration at four selected sites in London will exceed 400 $\mu g/m^3$ and 600 $\mu g/m^3$, or for all sites (in Manchester) 270 $\mu g/m^3$ and 450 $\mu g/m^3$. The criteria are set out in Table 1.

Inevitably within a city, mean concentrations over a day will vary from place to place, and an approximately log-normal distribution has been shown to exist. The concentrations forecast by these schemes for the 4 sites represent approximately the 75% level for London as a whole (i.e., 75% of the city will have concentrations less and 25% more). The mean for London is approximately 20% less than the 4-site forecast concentration value. The mean for Manchester is given directly by the scheme. The success of the scheme is illustrated in Tables 2 and 3.

The Actual Concentration Forecast Scheme (Part II)

The variation of concentration with the same meteorological parameters used in Part I was studied for the two winter periods for the London data and following formula yielded satisfactory estimates of the average concentration. Almost as good results were obtained when applied to the Manchester data.

$$C_{est.} = \left[1 + \frac{\delta_d}{5}\right]\left[1 + \frac{\delta_m}{6}\right]\left[1 - \frac{T}{20} + \frac{t}{20}\right](a\bar{C} + bC_p)$$

Where $\bar{C}$ = long term mean concentration

$C_{est.}$ = estimated concentration (24-hour average)

C_p = concentration for the previous 24 hours

T = minimum temperature (°C) expected up to midnight

t = number of hours of mean wind less than 3 knots during the 24 hours

$a = \frac{2}{3}$, $b = \frac{1}{3}$ if the mean wind for the day exceeds 6 knots

$a = \frac{2}{7}$, $b = \frac{15}{21}$ otherwise

δ_d = (1 if the mean wind comes from the "dirty sector,"
(060° to 120° in London only
(otherwise

δ_m = (1 if mixing depth is low
(0 otherwise

The Simplified Forecasting Scheme (Part III)

A simpler version of Part II was developed to help the operational forecaster by minimising the analysis required to obtain the parameters required in the scheme.

The formula is now:

$$C_{est.} = 0.085\left(1+\frac{\delta_m}{6}\right)\left(1-\frac{T-t}{23}\right)\left(5\bar{C}+4C_p\right)+0.15\,\bar{C}$$

where δ_m = 1 if the mixing depth is low for London only, and only, and is 0 otherwise

T = minimum temperature from 09 to 09

t = hours when mean wind falls below 5 kts

$\bar{C}$ = mean concentration

C_p = yesterday's concentration

This formula is expressed as a nomogram in Figure 1.

Results of Parts II and III

Table 4 summarises the results. The root-mean-square errors have been evaluated for the four sites over the two winters. The significance of the errors have to be assessed in relation to the inherent "error" due to local quasi-random variations in concentration at the four sites which can be estimated from the intersite correlations. The inherent error in the average concentration was shown to be about 50 $\mu g/m^3$.

The root-mean-square error in the formula-estimates is only 66 $\mu g/m^3$ (little more than the inherent error) if the actual value of C_p, the previous days's concentration is known and used, but rises to nearly 80 $\mu g/m^3$ when C_p is only known by the application of the formula using the actual meteorological data at the end of the previous 24-hour day. This is still a satisfactorily small margin of error when compared with the inherent error, and is certainly considerably less than that obtained using a persitence forecast (142 μg/m^3), i.e., by using yesterday's concentration as an estimate for today's. If E_t is the total error, E_i is the inherent error, and E_s is the basic error of the scheme, then:

$$E_t^2 = E_i^2 + E_s^2$$

For the whole of Inner London (nearly 100 sites), E_i will fall from 50 μg/m^3 to about 10 μg/m^3. The expected value of E_t would then be:

$$E_t^2 = (80)^2 + (10)^2 - (50)^2$$

The formula displays the relative importance of the basic parameters. It is clear then an error of 4°C in T , the minimum temperature, would introduce an error in C_w of about only 50 μg/m^3. A similar error would follow from an error of 3 hours in t , the hours of light winds, or of about 150 μg/m^3 in C_p. The method does not therefore demand impossible precision in evaluating the basic meteorological parameters.

Chapter XIX

WARREN SPRING LABORATORY

by

Dr. Alstair Keddie

Stevenage, Hertfordshire
England

3rd MEETING OF THE NATO/CCMS PANEL ON MODELING

WARREN SPRING LABORATORY
Gunnels Wood Road, Stevenage, Hertfordshire, SG1 2BX, United Kingdom

As urban air pollution modelling is really just getting under way at Warren Spring Laboratory, this contribution is more a statement of intent rather than a description of work already done.

The broad objectives of our work are to develop numerical models which can be used to: predict the effects of changing the emission characteristics of existing sources (eg changing the type of fuel or increasing the capacity of an industrial plant); assist planners in deciding how best to extend residential areas and site new industry; provide a better understanding of how to deploy air pollution sampling networks so that the maximum amount of meaningful information can be obtained from them.

Items of specific interest are: the relative contributions of low-level emissions (eg residential and transport), medium level emissions (eg general industry) and high-level emissions (eg power stations) to ground level concentrations of pollutants and also to the concentrations at various heights above the ground; the effects of topography, and urban structure on concentrations.

The types of model adopted will, in the first instance, be based on the "box" concept and on Gaussian type formulae. However, it is felt that this is a rather restrictive approach and it is intended to develop methods of numerically solving the diffusion equation, on a three-dimensional grid system, for the particular problem in hand. We also think that it will be easier to achieve a better understanding of the physics of the problem by adopting this latter method. In this context, considerable use will be made of our hybrid computing facilities, which will also be used for sensitivity analysis. A further use of the hybrid system envisaged is its application to the problem of finding the best location for a new emitter; as a first attempt at such a problem, the consequences of the various alternatives can be displayed visually and almost immediately.

Work actively in progress includes the estimation of the contribution made by a large manufacturing process to the ground level concentrations of sulphur dioxide in a town, and the prediction of the contribution made by airport emissions (heating, vehicle transport and aircraft movements) to concentrations outside the airport area plus a comparison with the contributions made by towns of various sizes. The largest project under detailed consideration is a combined survey/modelling exercise for part of the industrial belt of Central Scotland. This exercise will involve setting up a monitoring network to establish the current distribution of pollution and to validate a model for the area. The model will then be used to assess the effects of increasing the operating capacity of existing plants and to choose the best locations for new emitters.

/

Chapter XX

MATHEMATICAL SYSTEM FOR CALCULATIONS OF SPREAD OF AIR POLLUTION IN THE GREATER STOCKHOLM AREA

by

Björn Bringfelt, SMHI, and Olof Wikström

The Stockholm Electricity Board
Stockholm, Sweden

THE STOCKHOLM ELECTRICITY BOARD
1972-05-24

Mathematical system for calculations of spread of air pollution in the Greater Stockholm area.

by Björn Bringfelt, SMHI, and Olof Wikström, the Stockholm Electricity Board.

Introduction

In the Greater Stockholm area - as in all major urban areas - there is an increase in population concentration resulting in - inter alia - an increase in air pollution both totally and per surface unit.
The dominating impurities resulting from the combustion of oil consist of sulphur oxides - mainly sulphur dioxide - and soot. The release of sulphur dioxide causes two kinds of problem. Locally - near a pinpointed position or in a city - sulphur dioxide in the air can occur in concentrations which can be detrimental to health and which can cause damage to vegetation andmaterial.
Regionally the deposits of sulphuric acid causes accumulated changes in soil and in water and can thereby alter prevalent biological conditions. This problem is of a global nature since a large part of the acid deposits originate from sources beyond Sweden's frontiers, and the problem must be dealt with by reducing the discharge of sulphur within national and geographical boundaries.
The air's content of drifting matter and sulphuric dioxide is on the other hand affected to a far greater extent by local discharge than by discharge in distant areas. In order to limit the damaging effects of sulphur dioxide the sulphur content in fuel oil has been limited to max 1 % in Greater Stockholm and extensive plans for continued expansion of the district heating system are existent. Around the 1980s it is planned that the production of district heating will be carried out in large nuclear combined power and heating plants.

The improvements in the air pollution situation that various measures can achieve have hitherto only been roughly estimated. To create the prerequisites for good environmental planning the demands for better bases for estimating suitable measures have become more and more accentuated. After preparatory studies at the Swedish Meteorological and Hydrological Institute (SMHI) work was started in the spring of 1970 on developing, on the basis of foreign pattern, a mathematical system for calculating the spread of discharged matter and the existing content at ground level in a major city. Gradually the project - the first of its kind in Sweden - has been finalized to cover Greater Stockholm, and the first stage is a study of conditions in the city centre.

Since the matter in question is of great interest to the city's heating supplies, the Stockholm Electricity Board (SEB) and some district heating producing suburban municipalities have agreed to finance the first phase of the project in conjunction with the National Environment Protection Board (NEPB). Work is carried out under the direction of the National Environment Protection Board, while development and programming is done by the climatology section of SMHI. An emission inventory has been carried out by the Air Conservancy Department of the Nature Conservancy Board, the Stockholm Public Health Board, the County Administration in the County of Stockholm and 14 suburban municipalities concerned.

Sphere of application

There are primarily three fields in which it is estimated the system will be utilized.

- Planning for use of land where the use to which the various sites are to be put can be indicated (industry, highways, housing, green belts etc) in order to obtain optimum quality of air.
- The development of air conservancy programmes where indication can be given regarding which alternative control measures (a transition to lower sulphur content in fuel oil, a development of district heating, a temporary limitation on discharge during unfavourable weather situations etc) can give acceptable air quality.
- The system is intended to supplement monitor stations for air pollution. The system can be used to calculate content in areas where there are no monitor stations. It can be used to help determine whether new

monitor stations are required and if so where they should be located. A spread system offers the most effective utilization possible of existing measurements.

The spread system for Stockholm is the first system for an entire Swedish city. With the help of the system the share of content from several hundred facilities, even the smallest heating-plants, can be estimated. Methods of calculation used previously in Sweden only take into consideration share of content from one or a few major facilities.

Development of the system of calculation

Appendix 1 shows the progress of work in developing the system.

First meteorological data is prepared - source data, so called emission data and values for observed pollution content for a predetermined period with which the system is tested.

Thereafter a method is needed for estimating the pollution content on the basis of the meteorological data and the emission data. The actual system of calculation consists in this case of a collection of twelve computer programmes.

Wind and turbulence (meteorological data in app 1) carry and dilute (actual diffusion) released impurities (source data) which gives observed concentrations. With the help of the system the equivalent content in places where this has been observed (monitor stations) is calculated. The test is carried out by comparing estimated and observed content. In this way the system can be corrected and improved.

A new system which has been tested and corrected can then be utilized to calculate the pollution situation for various alternative planned amounts and positions of discharge which is of interest to test. It is then ready to be used for one or other of the purposes described previously.

Emission inventory

The sources of emission can be divided partly into a limited number of major sources, which we can call "pin-point sources", the position and emission conditions of which must be carefully charted, and partly in an unknown number of minor sources, which are grouped in "surface sources". These cause a background concentration, which could vary to a certain extent between different positions in the city.

Pin-point sources

Questionnaires were sent to facilities with heating-plant, mainly those with an oil consumption exceeding 400 m^3 p.a. In this way information was obtained on location, height of chimney and the amount of SO_2 emitted every 6 month period. Information was also obtained on floorage in sq m in the areas to which the facility in question supplies heating.

In the case of the calculations with the system that are now current, emission data from about 190 pin-point sources in the municipality of Stockholm was used. About 100 of these facilities were located in the city centre.

Surface sources

The emission of sulphur dioxide is estimated for various grid squares on a grid, where each grid square had a side of 500 m. In the first survey the calculations covered the city centre and part of Solna. This area constitutes 206 grid squares. At a later stage it is intended to extend the area to include the whole municipality of Stockholm and certain surrounding municipalities.

The sulphur dioxide originates initially from oil combusted to heat buildings. Oil consumption was assumed to be proportional to the heated surface in each grid square area. The first stage of the calculations therefore involved estimating the total "apartment area" in each square. In the case of the city centre there are figures for the apartment areas in an inventory carried out in 1968, tabulated by the real estate office according to blocks. The apartment area for each square was obtained by adding up the apartment areas of the blocks within the square.

From the total apartment area of each square the following were subtracted:

- the apartment area supplied from pin-point sources
- the apartment area heated by gas
- the apartment area heated by district heating.

This gave the area supplied solely from minor sources.

The total apartment area per real estate taxation district was also obtained from the Central Population Registration and Tax Charge Office (DFU) through the 1970 real estate taxation figures.

Sulphur dioxide emission in the city centre

The total amount of sulphur dioxide discharged was calculated on the basis of information supplied by the Swedish Petroleum Institute on the consumption of heavy and light oil in municipalities in the County of Stockholm.
Results indicated - inter alia - that c. 50 % of the sulphur dioxide resulting from the combustion of heavy-oil and 8 % of the sulphur dioxide resulting from the combustion of light-oil originates from the pin-point sources. On total about 30 % of the sulphur dioxide in the city centre originates from pin-point sources.

In the case of the surface sources the system calculation is based on SO_2 emission per 500 m x 500 m grid square in g/secs during the calculation period, i.e. 206 values.
In the case of both surface and pin-point sources a temperature function is included which indicates the dependence of emission on outside temperature. Also in both cases consideration is taken to the dependence of emission on the time of day. These graphs are appended (appendix 2).

Meteorological data

Meteorological data consists of wind direction, wind velocity, category of stability, height to blocking layer and outside temperature. This data is given as hourly averages for every hour of the calculation period.

Outside temperature is only used in estimating SO_2 emission for a current 24-hour period. The temperature regulates the amount of heat needed and the intensity of combustion so that cold weather requires intensive firing and gives high SO_2 emission readings.

Wind direction and velocity figures are obtained from hourly observations at Bromma airfield.
It is assumed that wind direction for each hour is the same over the entire city.
Wind direction and velocity determine where pollution is carried to. Dilution during transport of this pollution is determined by the stability of the air. Certain atmospheric conditions of stability, e.g. those prevalent on a sunny summer´s day, cause greater dilution than the conditions prevailing during a clear night. A very uneven ground surface, e.g. urban building, causes greater dilution than even terrain because of the turbulence created by the uneven profile. Four different categories of stability are used. The category assigned to a particular hour is determined with the help of wind velocity, cloud amount and cloud base - data obtained from Bromma airfield - and the height of the sun.
Cities are often covered in blocking layers. Under the blocking layer mixing is good and the impurities are relatively evenly distributed with altitude. Above the blocking layer the air is considerably purer. The boundary between these two areas of air is sometimes very clearly defined and can be observed from an aircraft. The altitude of the blocking layer is estimated on the basis of the temperature´s variation according to height, and of the temperature in the city centre.

Spread calculations

The system presupposes that every discharge is spread in the form of a uniform column of smoke. This column is assumed to move away in a consistent wind whereby it expands and is diluted by turbulence. See lefthand figure in appendix 3.
Ground level concentration at any place can now be estimated if the amount of discharge, the height of the chimney and the meteorological data are all known.

As we mentioned in connection with the emission inventory, the major sources (c. 190) are treated separately. The above information is used for each such individual source in estimating its content share. The minor discharges are replaced in calculation by chimneystacks arranged in 500 m x 500 m grid squares (surface sources). In each such square 10 x 10 = 100 chimneystacks are placed. Emission in each square is estimated from - inter alia - the number of heated sq m of floorage. Se section on emission inventory.
Since we have several sources, the content values from the various columns of smoke must be added. See righthand part of appendix 3.

The content values at each square's centre (206 points in the city centre) are estimated for 779 different meteorological categories. At this stage shares from major sources and surface sources are added up.
As mentioned previously the system is tested by comparing the values for the sulphur dioxide content measured at various monitor stations in the city with values estimated by the system on knowledge of meteorological data and emission strength. The period utilized for the introductory testing of estimated content consists of the month of December 1969 and the months of January, February and March 1970. Computer work is mainly done on SMHI's Saab D22. Most of the programmes take less than one hour to put through the computer.

Report on stage 1 - Stockholm city centre

Stockholm - like other major cities - has experienced a steady deterioration of air since World War Two. Admittedly pollution in the form of soot has diminished with the transition from coal and coke burning to oil-firing, but the SO_2 content in the city air increased considerably up to 1968 when demands for utilization of oil with a low sulphur content - max 1 % - were introduced. The many heating-plants with low chimneystacks and often poor combustion results contributed to the SO_2 content in various city areas often exceeding the National Environment Protection Board's standards. It was also soon determined that there was a direct connection between these high SO_2 contents and low outside temperatures.

It is pleasant to note that in recent years there has been an improvement in Stockholm. The primary reason for this is the transition to fuel oil with a low sulphur content and the concentration of the production of heating to a district heating plant in Värtan with effective combustion, effective dust collectors and high chimneystacks.

The distribution net, on which work started in 1960, is now extended so that district heating is available throughout Gärdet, in the greater part of Östermalm and Norrmalm and in bordering areas of Vasastaden. At present about 3.3 million sq m of living space are linked to the Värtan plant. This means that c. 20 % of the total living space in these areas of the city have district heating. For obvious reasons the proportion of district heating is greatest in areas closest to the plant.

Extensions during the Seventies are continuing at a rate equivalent to a twofold increase every fifth year and by 1980 Kungsholmen will also be receiving district heating from Värtan. The major part of the production of district heating will then be produced by a new combined power and district heating plant i Värtan producing 210 MW of electricity and 310 MW of heating. Maximum effect in the plant (at -20 °C) will in 1980 reach more than 800 MW according to prognoses.

With the help of the recently completed spread system over the city centre it is now possible to illustrate ground level SO_2 concentration for the whole area. In connection with the UN Conference on the Human Environment the projekt management has selected to present a comparison between the air pollution situation in Stockholm's city centre during a normal cold winter 1969/70 and the equivalent period 1979/80. Consideration has been taken to the previously mentioned extension of the district heating net which is illustrated in the form of marked houses which are linked to the district heating net at the time of the two periods in question. It has also been assumed that the same meteorological conditions will apply to both the periods studied.

Average values of SO_2 content during the winter period are set out as isolines on a map of the city centre. During the winter 1969/70

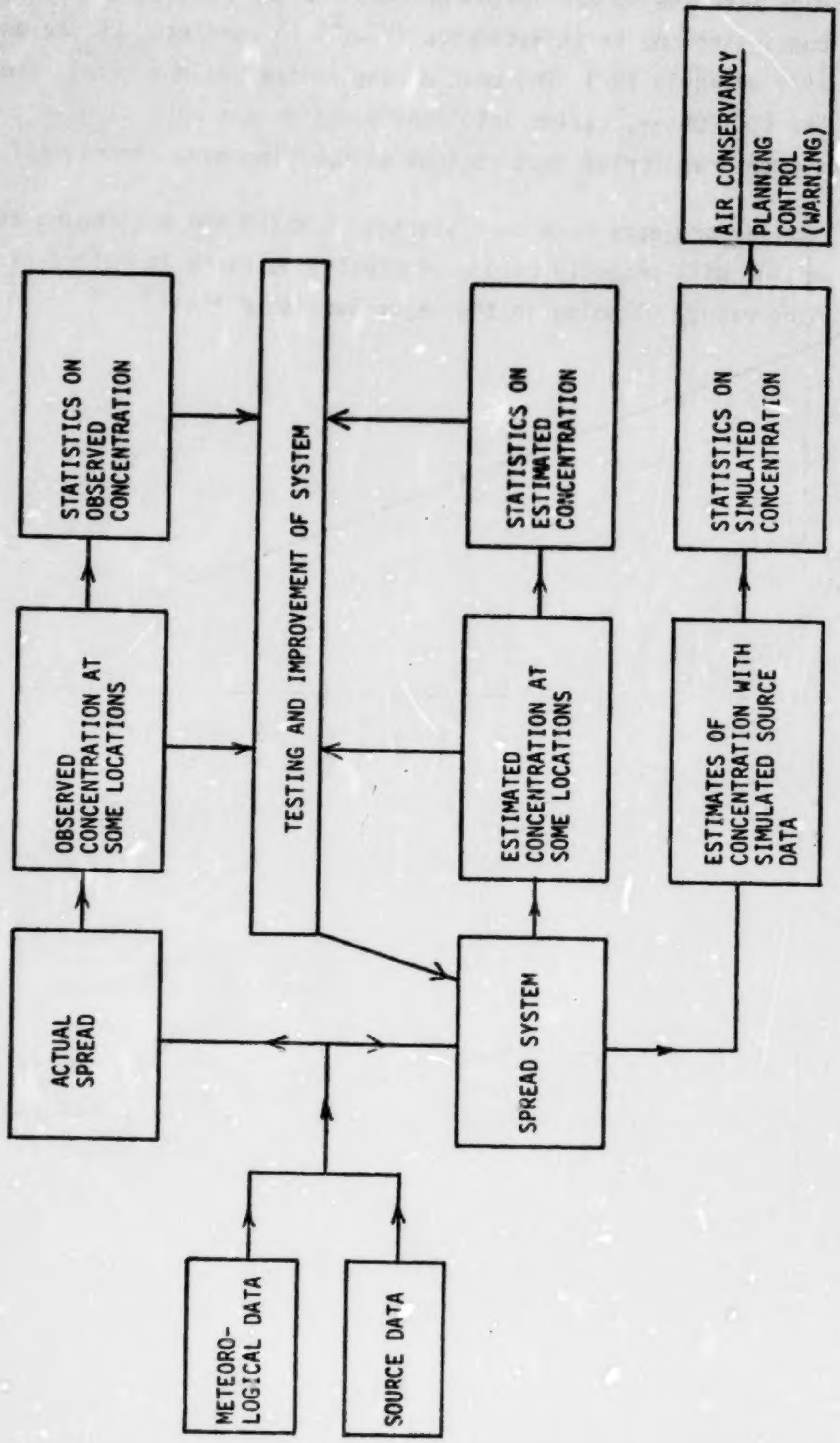
the highest readings occurred in Norrmalm (6.5 pphm SO_2) while Södermalm was down in c. 4.5 pphm. The wide extension of the district heating net in the northern sector of the city centre during the Seventies results in a very considerable reduction of SO_2 content at ground level in the areas with most district heating. In Norrmalm the maximum values have diminished by just over half to c. 3 pphm while conditions in Södermalm, which has no district heating, have been affected to a lesser extent. See appendixes 5 and 6.
These values can be compared with the National Environment Protection Board's recommendations for SO_2 content in outdoor air. These stipulate that monthly averages must not exceed 5 pphm.
Calculations are based on the major sources in the whole of the municipality of Stockholm and on the surface sources in the city centre. In the periphery of the area of calculation, calculated content can be expected to be to low since the content share from surface sources outside this area is not included in the estimates. In the centre of the area, where the monitor stations are located, local discharge can be expected to dominate and therefore the effect mentioned will be more or less negligible. Work is going on to extend the calculations to include complete emission in outer areas as well, and this will lead to more accurate estimates and also charting of a larger area.
Appendix 4 gives a comparison between two cumulative content frequency divisions. The unbroken graph is bases on measured 24-hour period values of SO_2 content (Torkel Knutssonsgatan 20), while the dotted graph refers to equivalent content estimated with the spread system. We can see that 10 % of the measured values exceed 7.5 pphm while 10 % of the estimated content is greater than 9.5 pphm. The high values are therefore somewhat overestimated by the system while the low ones are underestimated. The average value (50 % limit) is just under 4.5 pphm for both the measured and the estimated content. The estimated content like the measured content is virtually logarithmically normally distributed. (Straight lines in appendix 4).

Bearing in mind that this is the first estimate result from the spread system, the agreement between estimated and measured content must be considered good.

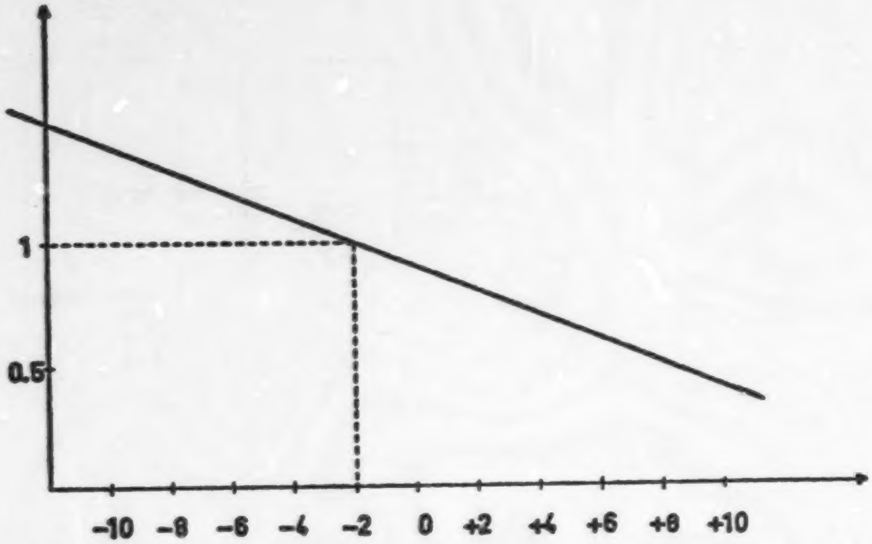
Work with the spread system for the whole of Greater Stockholm is continuing and it is estimated it will be completed by the end of 1972 or early 1973. The cost of the entire project totals around Skr 400.000:--, taking into consideration the extensive work on source inventories that various authorities have contributed.

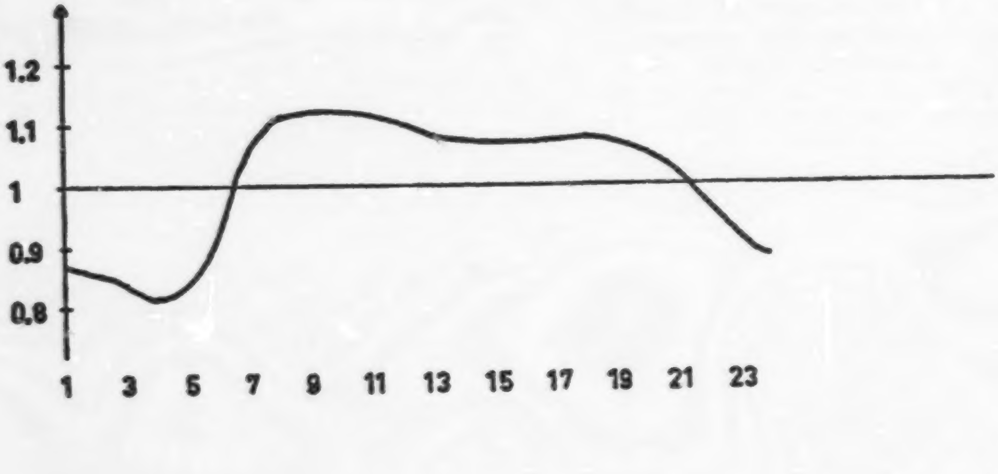
Similar projects have been started in Malmö and Gothenburg and the method will probably become of great importance to future air conservancy planning in the major Swedish cities.

FLOW CHART FOR THE DEVELOPMENT OF A SPREAD SYSTEM


METEORO-LOGICAL DATA
SOURCE DATA
ACTUAL SPREAD
SPREAD SYSTEM
OBSERVED CONCENTRATION AT SOME LOCATIONS
STATISTICS ON OBSERVED CONCENTRATION
TESTING AND IMPROVEMENT OF SYSTEM
ESTIMATED CONCENTRATION AT SOME LOCATIONS
STATISTICS ON ESTIMATED CONCENTRATION
ESTIMATES OF CONCENTRATION WITH SIMULATED SOURCE DATA
STATISTICS ON SIMULATED CONCENTRATION
AIR CONSERVANCY
PLANNING
CONTROL
(WARNING)

The upper graph indicates utilized link with the dependence of emissions on outside temperature. The lower graph indicates the dependence of emission on the time of day.





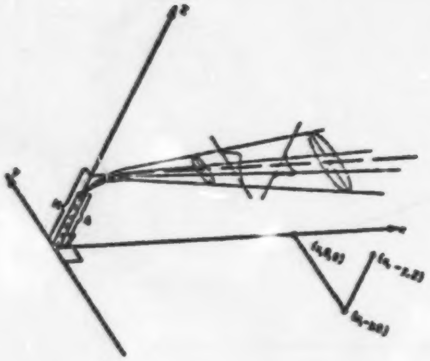


Illustration of a column of smoke leaving a chimney. The two "bell graphs" indicate content distribution on a horizontal and a vertical plane. The oval lines apply to equal concentration. As the diagram is drawn noticeable ground level content appears first at great distances - outside and to the right of the diagram. From TURNER 1969.

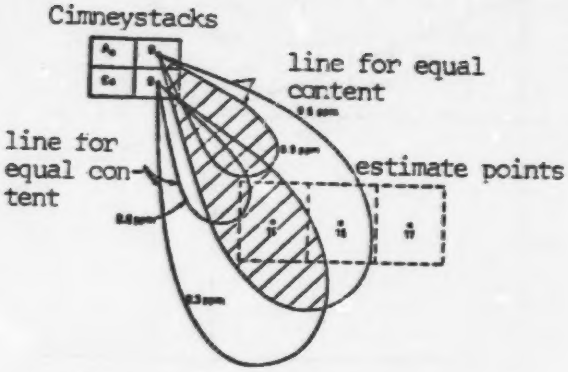
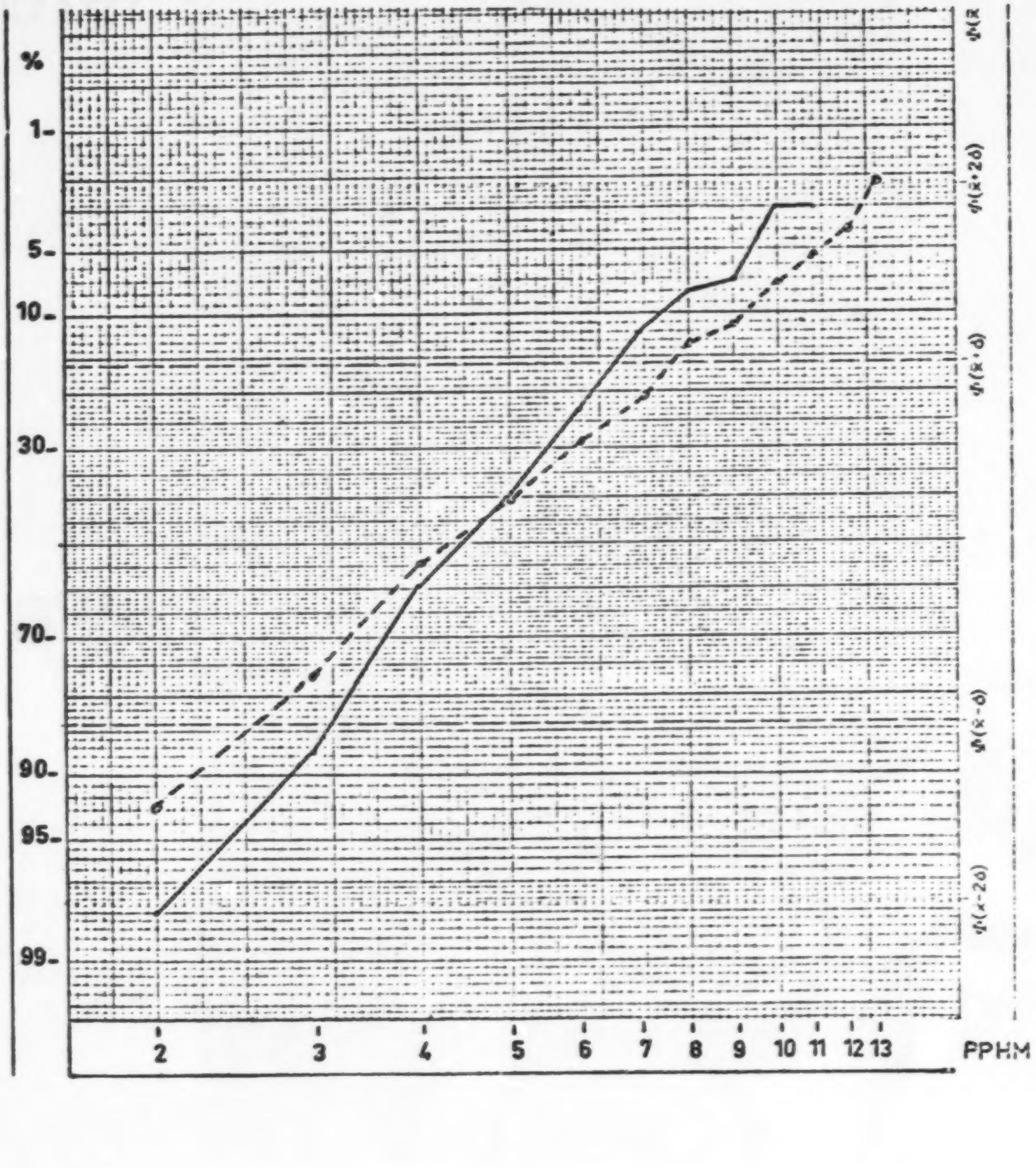
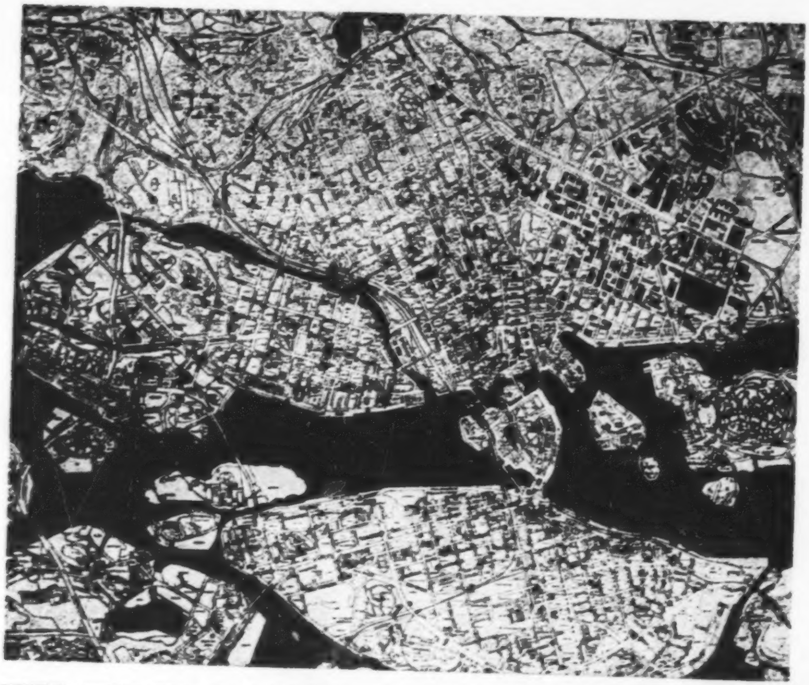

Cimneystacks
line for equal content
line for equal content
estimate points

Illustration of calculating technique in spread system. Chimneystacks located at A, B, C and D, estimate points at 15. 16 and 17. Within the line for 0.6 pphm SO_2 content from chimney B and the line for 0.3 pphm from chimney D (the shaded area) the content is greater than 0.9 pphm as is the case therefore at point 15. From MOSES 1969.

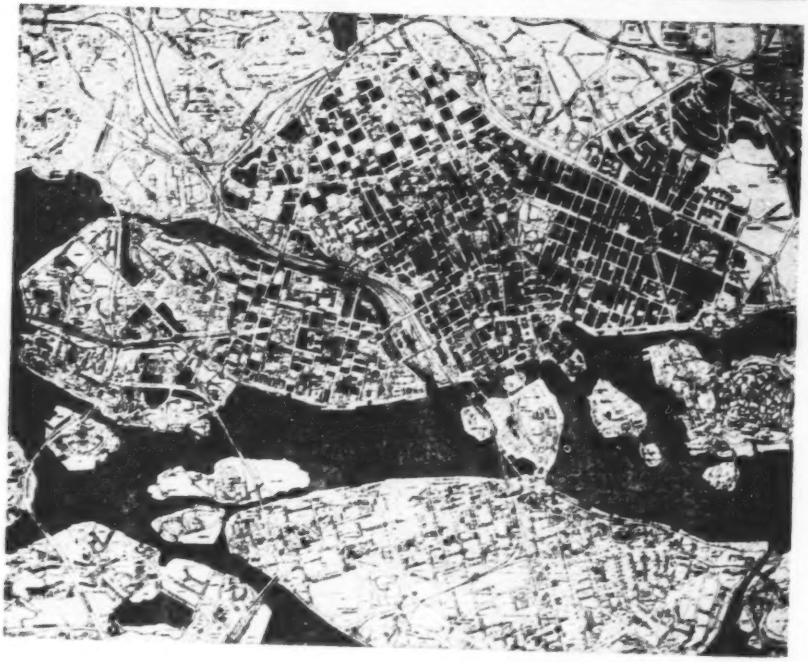
Comparison between observed (unbroken line) and estimated cumulative frequency distribution of daily average content of SO_2 at Torkel Knutssonsgatan 20. Dec 1969 - March 1970 (99 measured values per division).



DISTRICT HEATING EXTENSION

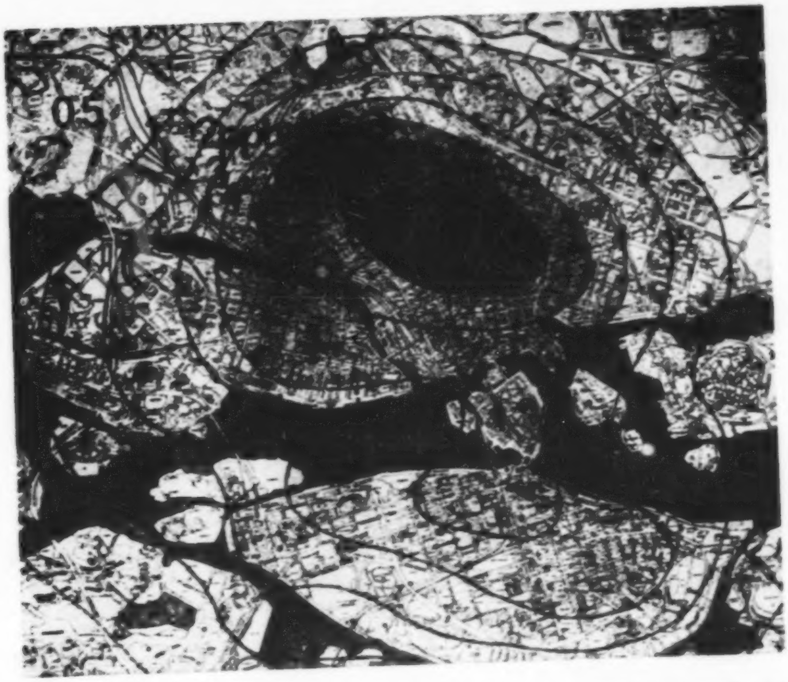


1970

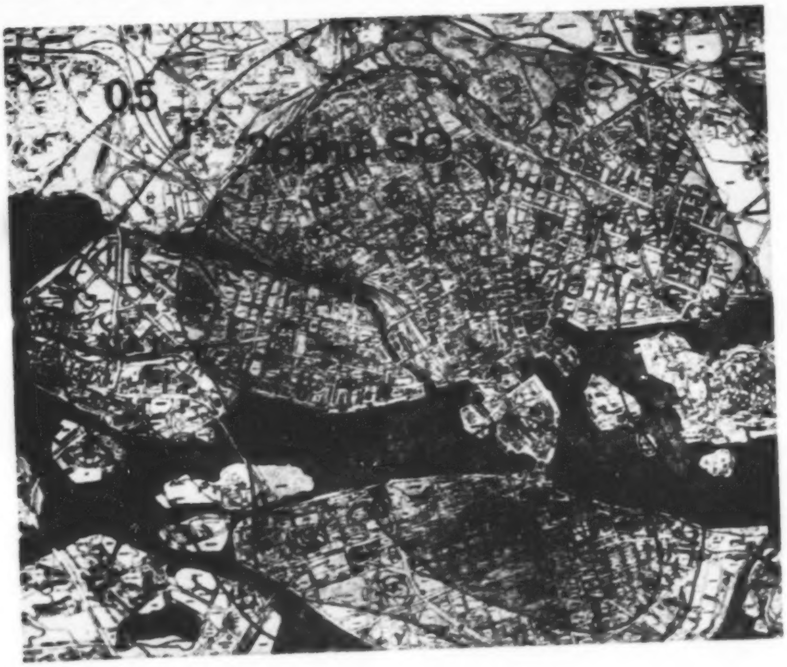


1980

SO_2 - IMMISSION



1970



1980

Chapter XXI

A COMPARISON OF STABILITY MEASUREMENTS TO PASQUILL-TURNER STABILITY CLASSES

by

Lars E. Olsson, Sture Ring and Sten Ljungkvist

The Swedish Meteorological and Hydrological Institute
Stockholm, Sweden

A Comparison of Stability Measurements to Pasquill-Turner Stability Classes

By Lars E. Olsson, Sture Ring and Sten Ljungkvist - The Swedish Meteorological and Hydrological Institute, Stockholm,Sweden

One of the major problem areas related to development and use of various atmospheric models involves usage of routine meteorological observations in describing the diffusion capability of the atmosphere. Ideally high resolution measurements of the temporal and spacial variations of turbulence intensity should be made by means of, e.g., tower mounted temperature and wind sensors. In lieu of such measurements Pasquill (1961) and Turner (1964, 1969) have developed methods for estimating the degree of dispersion of airborne materials using routine weather observations. Luna and Church (1972) have compared turbulence intensity and stability ratio measurements made by means of an instrumented tower with Pasquill-Turner stability classes based on observations made at a weather station. They conclude that, although, on the average, predictions using the mean values were fairly well correlated there was a large scatter of individual values.

In connection with development of regional dispersion models, further development of models for estimating stack heights and work on a ventilation climatology for Sweden, attempts are being made to refine the Pasquill-Turner scheme. By using 30 months of hourly stability and wind data recorded on a 122 meter tower and simultaneous hourly weather observations from a nearby weather station the effect of various observed weather parameters on the stability is being studied. Lapse rate and a Richardson type stability ratio described by Högström (1968) are used as dependent variables while insolation, cloud amount and type, wind speed and direction and possibly also past and present weather and visibility are used as independent variables in the study. Comparisons are also extended to include lapse rate and stability ratio data obtained from measurements made simultaneously by means of routine radiosonde.

The results obtained to date include comparisons between the frequency distributions, month by month, of specified stability ratio classes and standard Pasquill-Turner classes, specified lapse rate classes and standard Pasquill-Turner classes as well as hour by hour comparisons between these parameters. Our preliminary results are in general agreement with those reported by Luna and Church (1972). Further investigations with modified Pasquill-Turner classes do however suggest that it will be possible to improve the Pasquill-Turner scheme by including other variables and possibly also by using different schemes depending on season and time of the day. There is, furthermore, evidence that geographic location and topography should be included amongst the independent variables. Stepwise regression analysis is now planned to determine which variables should be used in an optimized Pasquill-Turner class scheme.

Our hope is that some of the results we will be able to present at the meeting will be of general interest and that the participants at the meeting will help direct our investigation in the most fruitful direction. As we continue to base so much of our modeling effort on the Pasquill-Turner type stability classificaton it seems logical to further investigate and hopefully improve these classifications.

References:

Högström, U., 1968: A Statistical Approach to the Air Pollution Problem of Chimney Emission, Atm. Env., 2; 251-271.

Luna, R.E. and Church, H.W., 1972: A Comparison of Turbulence Intensity and Stability Ratio Measurements to Pasquill Stability Classes. Journ. Appl. Met., II; 663-669.

Pasquill, F., 1961: The Estimation of the Dispersion of Windborne Material. Met. Mag., 90, 33.

Turner, D.B., 1969: Workbook of Atmospheric Diffusion Estimates. Publ. No. 999-AP-26, Public Health Service.

Chapter XXII

A THREE-DIMENSIONAL TRANSPORT MODEL FOR AIR POLLUTION IN AN URBAN AREA WITH APPLICATION TO SO_2 CONCENTRATION IN OSLO

by

Knut Erik Grønskei

Norwegian Institute for Air Research
Kjeller, Norway

Oppdragsrapport 41/72
Reference: EO 000769

Forward

The work presented in this paper is a part of a larger investigation of the SO_2 concentration in Oslo. The leader of the project has been E. Joranger. The project has been financially supported by the oil companies in Norway.

Table of Contents

Page

1. Introduction XXII-4

2. Mathematical Formulation of the Model XXII-6

3. Description of the Oslo-Region and the Measurements in Oslo . XXII-10

4. Wind Model for Oslo XXII-13

5. Calculation of the Concentration of Sulphur Dioxide XXII-28

6. Conclusion XXII-37

References XXII-39

Introduction

The Norwegian Institute for Air Research (NILU) has performed an investigation of the ambient air concentration of SO_2 in Oslo, and its relation to emission and weather conditions.

During the period 1959/1963, the SO_2 concentration has been measured in Oslo by W. Lindberg (1). NILU's investigation was financially supported by the oil companies in Norway, and the intention was to establish the trend in the ambient SO_2 concentration from this period to the winters 1969/70 and 1970/71. Further, the intention of NILU's investigation was to develop a model that described the connection between the emission of SO_2, the ambient air concentration and the weather conditions (wind and temperature stratification).

To establish this connection in a realistic way, it was found necessary to study representative short term variations in the SO_2 concentration. As far as the author knows, this has not been done before with reportable success. Instead, work has been carried out to model longer term average concentration which is important in air quality considerations.

In many of the applied models, a Gaussian diffusion formulae is used to estimate the dispersion from a large number of single point sources or groups of point sources within the urban area (2)(3). A Gaussian diffusion formula is known to describe well the dilution of pollutants under certain simplified wind conditions. On the other hand, these simplified wind conditions are not realistic in an urban area. The existence of a convergence zone over the center of the city is well known (4), and this ought to be taken into consideration.

The pollution concentration in an urban area depends on both meteorological and chemical processes within the area. Emission of pollutants is often connected to emission of heat. In that way, both the chemical and meteorological conditions are changed due to the emission. The extrapolation of measurements of the ambient air concentration to other conditions of emission is difficult without knowing the importance of the different processes that cause these changes.

In a comprehensive system approach to abatement strategy, the connection between a reduction in emission and the change in ambient air concentration is approximated by a linear relationship (5). The air quality standards are set according to biological effects that primarily depend on the concentration near the ground. When a local problem is considered, it is the ground level concentration that has to be taken into account. On a larger scale, the total emission has to be considered together with the cleaning processes of the atmosphere.

In the city of Olso, we are studying a local air pollution problem. The horizontal transport of pollution will not carry the pollution away from the ground level although it will be diluted. Systematic vertical motion will transport the pollution away from the ground level more rapidly. Therefore, it is important to estimate the relative significance of these two transporting components.

It is rather difficult to analyse the chemical processes that lead to a transformation of the pollution components. As a first approximation, we have estimated a sink of SO_2 in Oslo to be dependent on the SO_2 concentration alone.

H. Reiquam was the first to perform model-calculations in Oslo during his stay in Norway in 1968 (6). These calculations showed that the use of a finite grid system (a box model) might be useful in Oslo. It might be said that we contined his work in our model studies during the winters of 1969/70 and 1970/71. A preliminary model was established and tested after the first winter, as a numerical solution of the continuity equation, applied to SO_2 as the pollution component (7). A stream-function was used to describe the horizontal windfield, and a sink term was made proportional to the concentration. The vertical flux of SO_2 was incorporated in this term as a first approximation, and the factor of proportionality was made dependent on the vertical temperature stratification. The value of this factor was chosen in order to match the observed and calculated concentrations. The factor had to be given a very high value which indicated that systematic vertical motions are important as a transport component. This conclusion was supported by detailed wind observations in a number of case studies.

Mathematical Formulation of the Model

As a mathematical frame for our model studies, the continuity equation for the pollution component (eq. 1) is used.

$$(1)\quad \frac{\delta q}{\delta t} = -\nabla_h \cdot (\vec{v}_h q) - \frac{\delta}{\delta z}(wq) + \nabla_h \cdot (K_h \nabla_h q) + \frac{\delta}{\delta z}\left(K_z \frac{\delta q}{\delta z}\right) + \text{sources} + \text{sinks}$$

t : time

x, y, z : orthogonal coordinates with unit vectors, $\vec{i}, \vec{j}, \vec{k}$

q : pollution concentration

K_h, K_z : horizontal and vertical diffusion coefficients

$\vec{v}_h = u\vec{i} + v\vec{j}$: horizontal velocity

$\nabla_h = \vec{i}\frac{\delta}{\delta x} + \vec{j}\frac{\delta}{\delta y}$: horizontal gradient operator

w : vertical velocity

In an urban area, there exist a lot of small sources at different levels up to a certain height H. Within this area the buildings and the heat sources at different levels lead to enhanced turbulence and a mixing of the air. In the computations, the mean concentration in this lowest part of the atmosphere is considered.

The equation is integrated vertically:

$$(2)\quad \frac{\delta \bar{q}}{\delta t} = -\overline{\nabla_h (\vec{v}_h q)} - \frac{(wq)_H}{H} + \overline{\nabla_h \cdot (K_h \nabla_h q)} + \left(\frac{K_z}{H}\frac{\delta q}{\delta z}\right)_H + \overline{\text{sources}} + \overline{\text{sinks}}$$

(-) : the mean value in the lowest part of the atmosphere with height H.

The horizontal windfield is separated in two parts. One divergent ($\vec{v}_\chi$) and one non-divergent part ($\vec{v}_\psi$)

$$(3) \quad \vec{v}_h = \vec{v}_\chi + \vec{v}_\psi \;; \quad v_\chi = \nabla_h \chi \;; \quad \vec{V}_\psi = \vec{k} \times \nabla_h \psi$$

The divergent part is described by a velocity potential χ and the non-divergent part is described by a stream function ψ. Observed winds at the boundary are used to estimate the stream function along the boundary after correction with respect to the divergent part of the velocity.

A town represents a permanent heat source relative to its surroundings, and will cause vertical motions. As a first approximation it is proposed to put the horizontal divergence ($\nabla_h \cdot \vec{v}_h$) proportional to heat sources or some parameter describing the heat sources.

$$(4) \quad \nabla_h \cdot \vec{v}_h = \nabla^2 \chi = a \cdot Q$$

Q : heat sources in the region
a : empirical factor of proportionality

The factor of proportionality must be estimated enpirically for each region.

The separation of the horizontal wind field into one convergent and one non-convergent part is not yet properly defined. As a starting point, the velocity potential is defined to be zero along the boundary. It may be shown that in this way, the kinetic energy connected to the convergent part of the velocity is kept at a minimum.

The effect of meteorological processes on a larger scale are taken into consideration by measuring or estimating the wind along the boundary. The measured boundary values are adjusted with respect to the convergent wind-field. The remaining part is used to estimate the stream function along the boundary. To estimate the stream function within the region, the following equation is sued:

$$(5)\ \nabla^2\Psi = 0$$

A way to estimate the vorticity within the region has not been found without taking a more complete set of the hydrodynamical equations into consideration. The intention of the present wind approximation is to calculate the air pollution concentration within an urban area, and it is believed that this concentration is strongly dependent on the vertical motion, but not very sensitive to small changes in the horizontal wind direction. The mentioned approximations represent a better approximation than the assumption of an homogeneous wind-field in the urban area, when the wind-field is weak.

A finite difference approximation of equations (2), (3), (4) and (5) may be used as a mathematical frame for the study of short term air pollution variations in an urban area.

Forward differences in time combined with upwind differences in space seem to be appropriate for eq. 2 if slow fluctuations in the concentration are considered. In an urban area, this often represents the more important variations. A relatively large artificial diffusion is built into the finite difference form. On the other hand, this form is simple, stable and ensure mass consistence.

Description of the Oslo-Region and the Measurements in Oslo

The Oslo region is shown in Fig. 1. The urbanized area is concentrated in about 60 km^2 and about 400,000 people are living there. The city of Oslo is surrounded by hills (height [illegible]-500 m) on one side, and the Oslofjord on the other.

During winter time, this system of topography and local heat sources induce a local wind system that may create air pollution problems. This happens during inversion situations and, statistically, a close connection is found between the vertical temperature gradient and the SO_2 concentration (8).

Six termographs were placed along the hillside of Holmenkollasen and were used together with the temperature recordings at the permanent meteorological stations to estimate the vertical stratification.

The site of the continuous wind measuring stations (V_1, V_2, V_3 and V_4 on Figure 1) were chosen in order to measure the wind through the main valleys. Beside, two wind stations were placed in the center of the city in addition to the permanent meteorological stations at Blindern (V_6) and Fornebu (V_7).

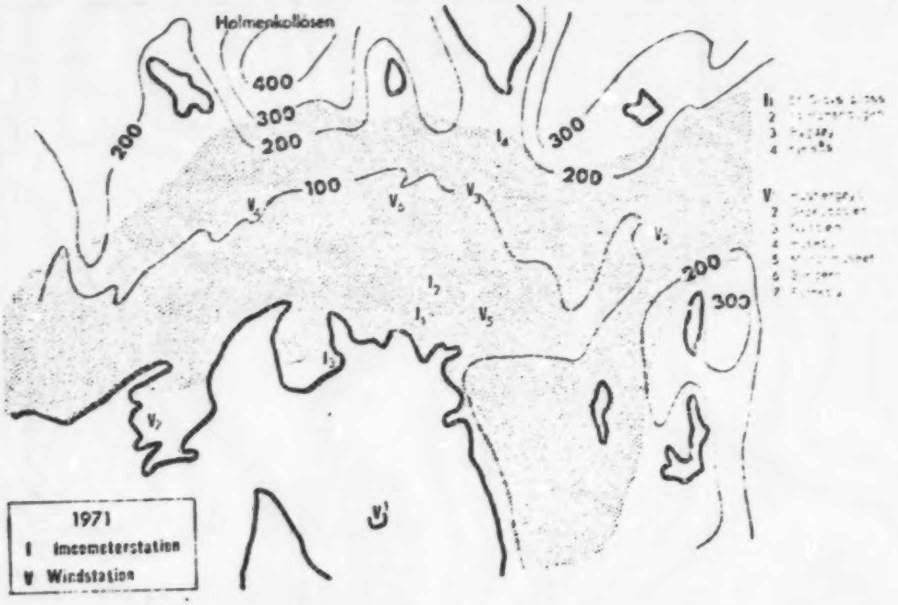

Holmenkollösen
400
300
200
100
300
200
200
300
1971
I imcometerstation
V Windstation

Fig. 1: The area of Oslo with measuring stations

The air quality survey consists of 25 stations measuring the daily mean SO_2 values together with the dust on filter (by light reflection). At four stations, the mean SO_2 concentration was measured each half hour (Braun and Lübbe imcometer). The imcometer and wind stations are marked in Figure 1. Two of them are placed in the center of the city, while the other two are placed north and south of this center respectively,

These measurements were adapted to the model studies and the observation region is divided into a grid system shown in Figure 2. The regions with high elevation are excluded from our computations.

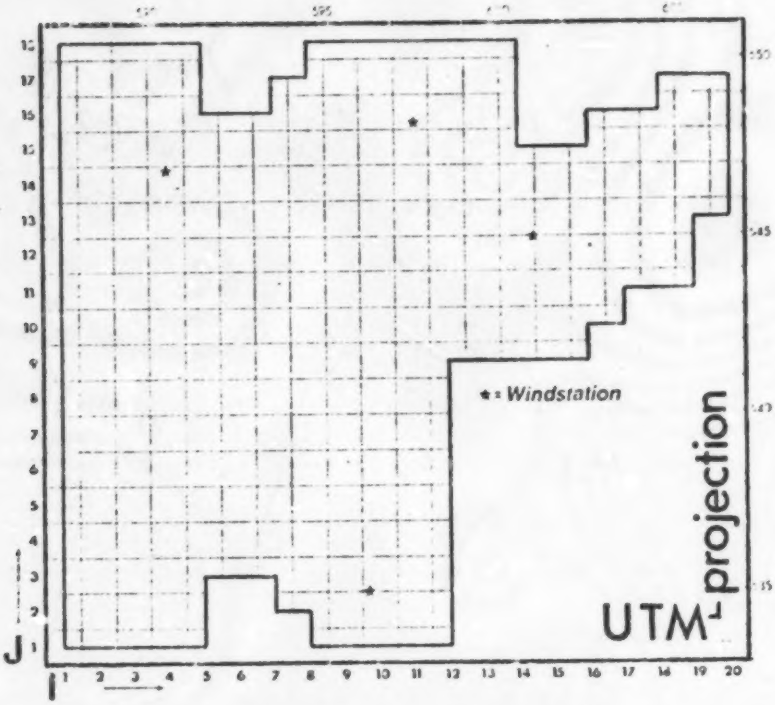

595
★ = Windstation
UTM-projection
J
I
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Fig. 2: The grid system

The grid distance is 1 km, and, in the finite difference approximation of eq. 2, a forward time step and an upwind finite difference system were used.

The finite difference approximation introduces an artificial diffusion. Reasonable estimates of the actual diffusion coefficients indicate that the diffusion term in equation 2 is small, compared with the artificial diffusion on a km scale. Therefore, the diffusion terms are left out of the computations.

An emission inventory up to 1970 was carried out by the oil companies in Norway. A result of this inventory has been an estimation of the delivery of sulphur in oil to each square km within the region during the first three months of 1970. This estimate is shown in Figure 3.

These data were extrapolated to the first three months of 1971, using data from the oil companies. The result is given in Figure 4.

To obtain a better understanding of the emissions and their time fluctuations, inquiries were made to a number of large oil consumers in the region. Although the investigation is not finished yet, it was found acceptable to use the data as an estimate of the SO_2 emission in the model calculations. There are uncertainties, but it is not believed that these will have any large influence on the computation.

The emission survey has also shown that the emission of SO_2 in Oslo is mainly due to domestic heating. There exists a large number of small sources and few isolated stacks. The emission height is connected to the height of the houses in the region. In this way, the sources of SO_2 in the Oslo region may be considered as volume sources and the height of the volume is connected to the maximum emission height in each square (1 side: 1 km).

Wind Model for Oslo

In order to estimate the wind field along the ground in Oslo from the permanent net of wind measuring stations, detailed investigations of the wind and temperature field were performed in 11 separate case studies.

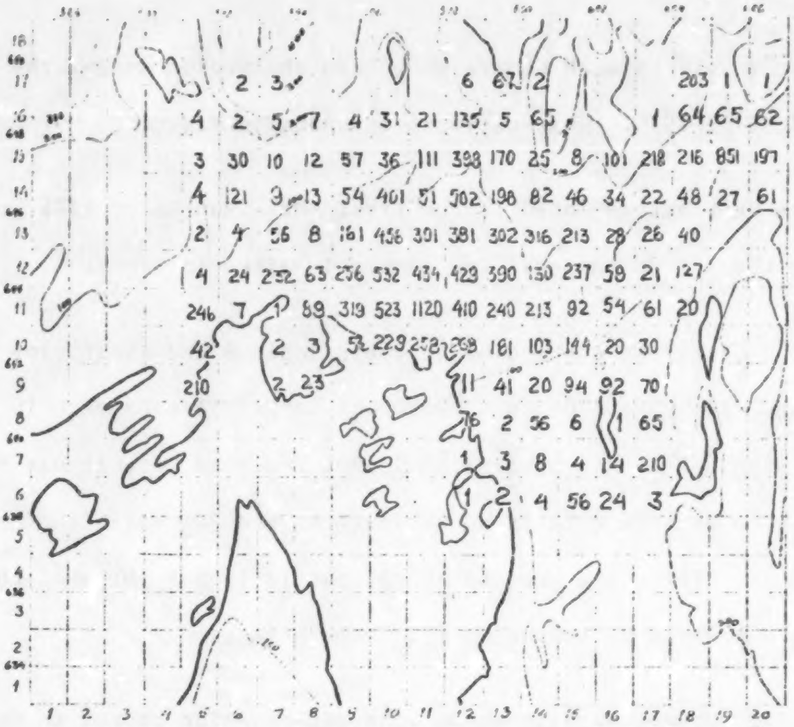

18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
2 3 6 67 2 203 1 1
4 2 5 7 4 31 21 135 5 65 1 64 65 62
3 30 10 12 57 36 111 398 170 25 8 101 218 216 851 197
4 121 9 13 54 401 51 502 198 82 46 34 22 48 27 61
2 4 56 8 161 456 301 381 302 316 213 28 26 40
4 24 252 63 256 532 434 429 390 130 237 58 21 127
246 7 1 89 319 523 1120 410 240 213 92 54 61 20
42 2 3 52 229 252 269 181 103 144 20 30
210 2 23 11 41 20 94 92 70
76 2 56 6 1 65
1 3 8 4 14 210
1 2 4 56 24 3
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure 3 Delivery of sulphur in oil Jan.-March 1970 (100 kgS/km²)

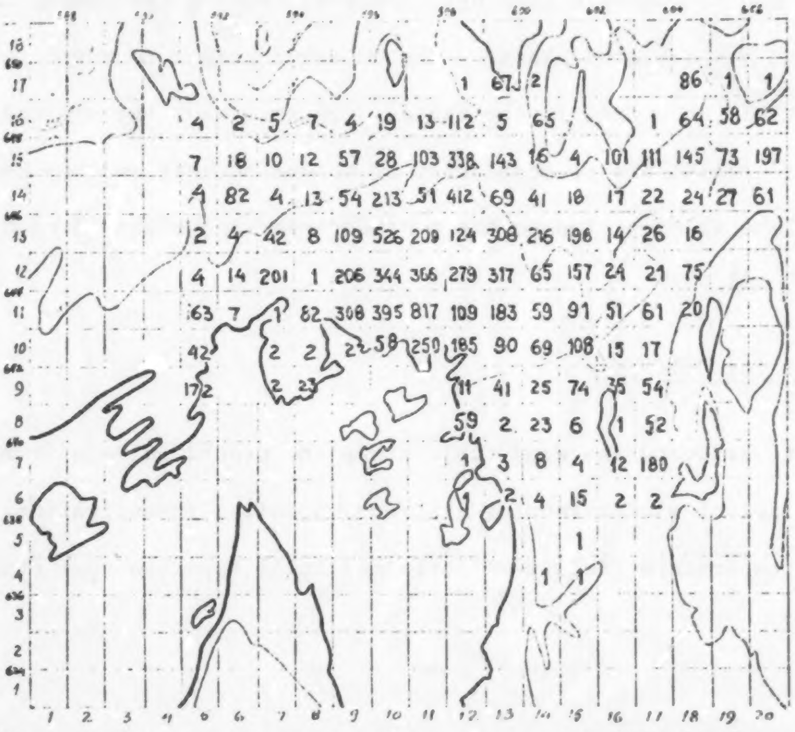

18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1 67 2 86 1 1
4 2 5 7 4 19 13 112 5 65 1 64 58 62
7 18 10 12 57 28 103 338 143 16 4 101 111 145 73 197
4 82 4 13 54 213 51 412 69 41 18 17 22 24 27 61
2 4 42 8 109 526 209 124 308 216 196 14 26 16
4 14 201 1 206 344 366 279 317 65 157 24 21 75
163 7 1 82 308 395 817 109 183 59 91 51 61 20
42 2 2 22 58 250 185 90 69 108 15 17
172 2 23 11 41 25 74 35 54
59 2 23 6 1 52
1 3 8 4 12 180
1 2 4 15 2 2
1
1 1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Fig. 4 Delivery of sulphur in oil January-March 1971 (100 kgS/km²)

In these case studies, cars were used along specified routes to measure wind and temperature. In this way, the wind and temperature fields in the area were measured within two hours. The wind variation with height was measured with a wire sonde. The wire sonde registration showed that the net of thermographs along the hillside of Holmenkollen measured vertical temperature stratification fairly well when local effects on single ground stations were taken into consideration. In inversion situations, a shallow atmospheric layer with neutral temperature stratification was observed over the center of the city.

Films and photographs were also used to a large extent in the case studies to register the extent of the air pollution. From this material, it was pointed out that there exist a systematic lifting of the pollution in the area (9). Along the ground level, a more or less well developed heat island (1-3°C) was found in the center of the city.

On cold days, the open Oslo-fjord represents a considerable heat source and a convergence zone in the area.

The windfield was thoroughly analyzed on the 18th of December 1970 and on the 6th of January 1971. An estimation of the divergence along the ground showed that this was mostly negative. Further, it seemed to be a reasonable approximation to set the convergence proportional to the emission of SO_2 over the city and proportional to the temperature difference between air and water over the open Oslo-fjord. The empirical manifestation of equation (4) in Oslo was:

$$(6)\qquad \nabla \cdot \vec{V}_h = \nabla^2 \chi = \begin{cases} a_1\ Q_{SO_2} & \text{over the centre of the city.} \\ a_2\ (T_A - T_W) & \text{over the open Oslo-fjord, when } (T_A - T_W) < 0 \end{cases}$$

Q_{SO_2}: areal sources of SO_2 in the region

$T_A - T_W$: Temperature difference between air and water

a_1 : $- 1{,}5 \cdot 10^{-5}\ s^{-1}\ (\text{ton } S/(km^2 \cdot 3 \text{ months}))^{-1}$

a_2 : $+ 3{,}0 \cdot 10^{-4}\ s^{-1}\ deg^{-1}$

The values a_1 and a_2 are regarded as empirical estimates of the combined effect of gravitational forces and heat sources in the area. It is believed that a_1 and a_2 are functions of other meteorological parameters within the region (f. ex. inversely proportional to the stability in the air), but no definite relationship of this kind was found in the present investigation.

To estimate the stream function describing the non-divergent wind field in Oslo, the wind measurement from each of the valleys was used. The wind observations were corrected with respect to the convergent wind field, and the corrected measurements on Husbergøya V_1, Groruddalen V_2, Nydalen V_3 and Husby V_4 were used to estimate the stream function, along the boundary, in their neighborhood. No air stream was allowed to cross very steep hillsides (for example Holmenkollasen).

The computed and measured wind directions in the area are compared in 11 case studies. In the Fig. 5-15, the arrows (↑) show the calculated wind directions in each grid point. The hached arrows show observed wind directions at the region time. The observations are mainly built on the drifting of smoke from Chimneys (10-20 m above ground level), but also on the drift of soap bubbles about 2 m above the ground. In the lower right part of the Figs. 5-15, the measurements from the termographs show the dependence of temperature on height. Date and time of the case study is given on each figure (5-15). A short description of the calculation and observation in each of the case studies are given.

Case Study 1: 7:00 p.m., 11th December 1970 (Fig. 5)

The weather was foggy, and there was a stable temperature stratification. The air movements are mainly from the south, and it is seen that a point of stagnation is moved to the north, relative to the maximum convergence zone over the center of the city and the fjord according to eq. 6. In the north-eastern valley (Groruddalen), the wind is weak and undefined.

The main features of the observations are comparable to the computed values. Near the fjord in the western part of the area (Lysaker), the observed wind direction is towards the fjord while the computations show an air flow from the fjord. On the other hand, the computations are comparable with the observations made in the north-western part of the area.

The difference between the observed and calculated values is probably due to local canalizing effects and a katabatic effect between the warm fjord and the cold land. An increase in the heat source effect of the fjord that would be necessary to attain the observed picture would be unrealistic.

Case Study 2: 12:00 a.m., 18th December 1970 (Fig. 6)

The fjord does not represent a heat source in this case because of the high air temperature. The cooling effect of the fjord will probably be effective only in a shallow part over the water and it is not believed to have any impact on the general wind field in the area. The vertical temperature stratification is stable (1 deg/100 m) with a neutral part over the center of the city. The point of stagnation falls together with the maximum zone of convergence over the center of the city.

The main features of the observed and calculated wind fields correspond. In the area over the fjord, there are discrepancies that might be due to special effects over the fjord that are not taken into consideration.

Case Study 3: 11:00 a.m., 4th January 1971 (Fig. 7)

The vertical temperature stratification in the area is stable with a neutral part over the center of the city. The general wind field shows a weak wind from the west. Because of this, the stagnation point is moved north-eastwards, relative to the maximum convergence zone. In this case, the observed and calculated winds correspond well.

Case Study 4: 3:00 p.m., 5th January 1971 (Fig. 8)

Largely, the temperature stratification seem to be neutral up to more than 200 m above sea level. Above this level, the air masses seem to be

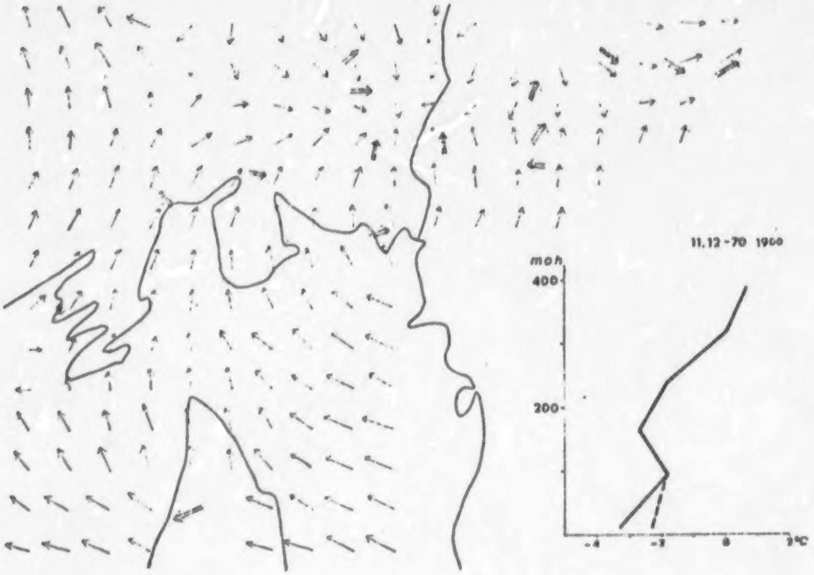

11.12 -70 1900
moh
400
200
-4
-2
0
2°C

Fig. 5

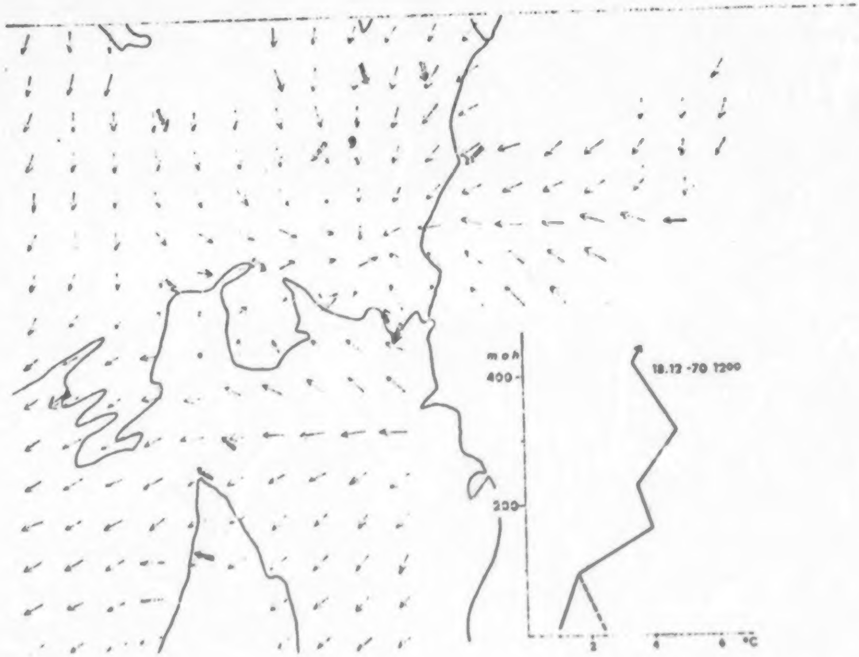

18.12 -70 1200
moh
400
200
2
4
6 °C

Fig. 6

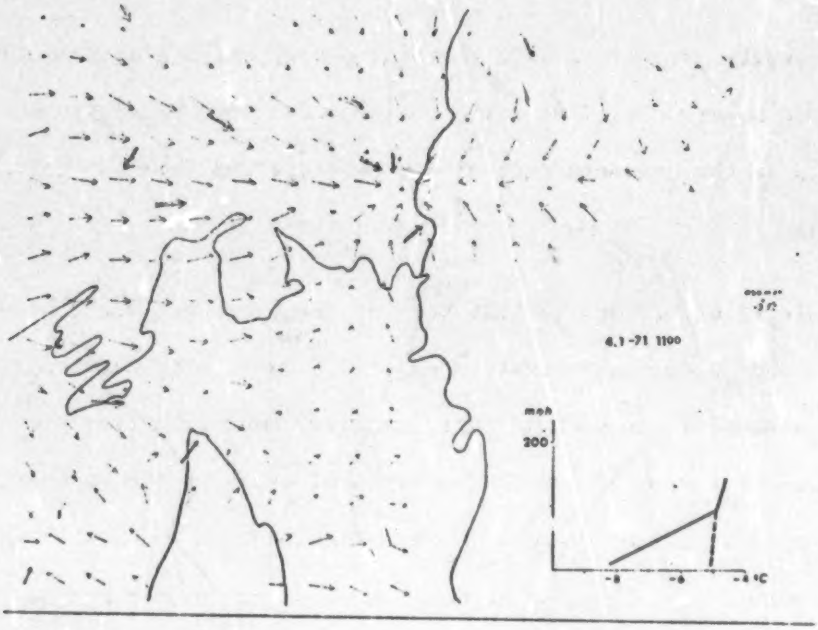

6.1 -71 1100
moh
200
-8
-6
-4 °C

Fig. 7

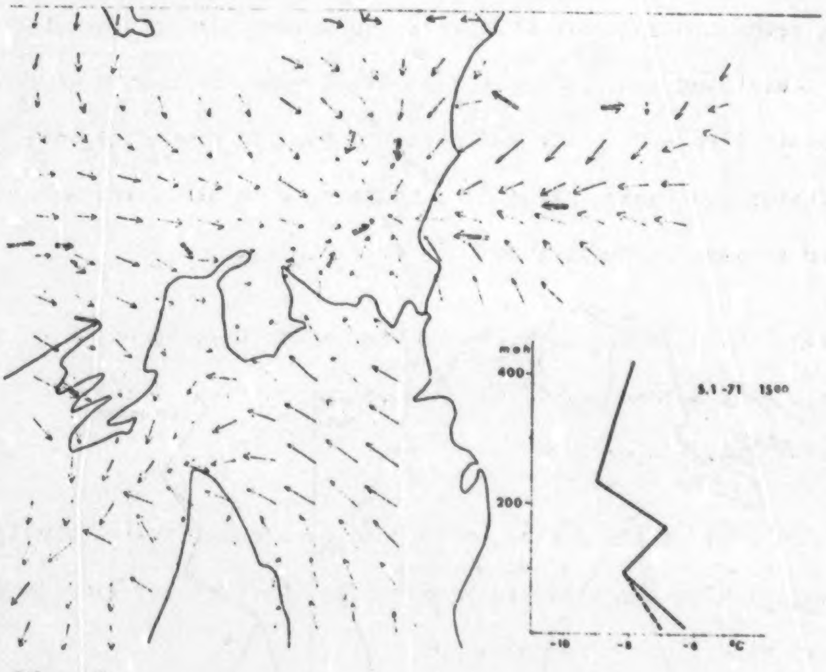

moh
400
200
5.1 -71 15^{00}
-10
-8
-6
°C

Fig. 8

stable. Generally, it may be said that the correspondence between the calculated and observed wind directions are good. An observation at the peninsula in the southern part of the area differs from the calculated wind direction.

The computed wind directions in that part of the fjord are due to the wind observation in the south-eastern part (V_1) and to the compensation zone in the south-western corner. The computed wind velocities over the fjord are very weak, and if one of the measured winds at the boundary is not representative, it may change the wind direction in the south-western area completely.

Case Study 5: 10:00 a.m., 6th January (Fig. 9)

The air was very cold and very stable in the lowest part of the atmosphere. A very well developed heat island was observed over the center of the city. Besides, an air stream from the north-east along the ground is well developed (katabatic wind). In this situation, some serious discrepancies are observed between calculated and observed winds.

In the eastern and southern part, the correspondence is good. Over the center of the city a tendency of stagnation is observed that is not computed. This may be of local importance.

In the western part of the region, a calculated stream towards the fjord does not compare with the observed winds. The observed air flow is directed along the isoterms where no heat sources exist and, in this way, there is correspondence between the wind and temperature observations in the area.

It might be noted that the wind blows along the direction of the geological structures in the area, and that small valleys might have a canalizing effect when the stability is high.

The rotation of the earth (Coriolis-force) may have an effect on the air streams in the area and explain the discrepancies.

Case Study 6: 1:00 p.m., 29th January 1971 (Fig. 10)

The vertical temperature stratification is near neutral. The computed and observed values compare well at 1:00 p.m. On the other hand, the wind field is not stationary. The observed and calculated wind field earlier in the day did not compare well. The present model does not cover transient wind fields. This is evident for example by the compensating zone in the south-western corner of the region and by the approximation of quasi stationary conditions.

Case Study 7: 12:00 a.m., 4th February 1971 (Fig. 11)

The vertical temperature stratification seems to be very stable in the lowest part of the atmosphere (6 deg/100 m). The air flow comes mainly from the south. The wind force is high enough so that no stagnation point is observed over the center of the city. It seems that the wind station in

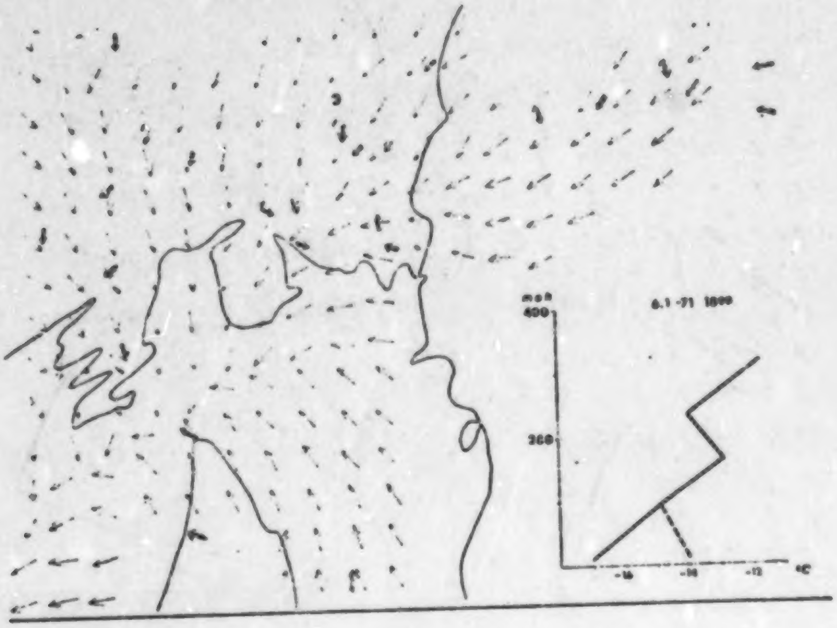

m
400
200
6.1 -71 1800
-16
-14
-12
°C

Fig. 9

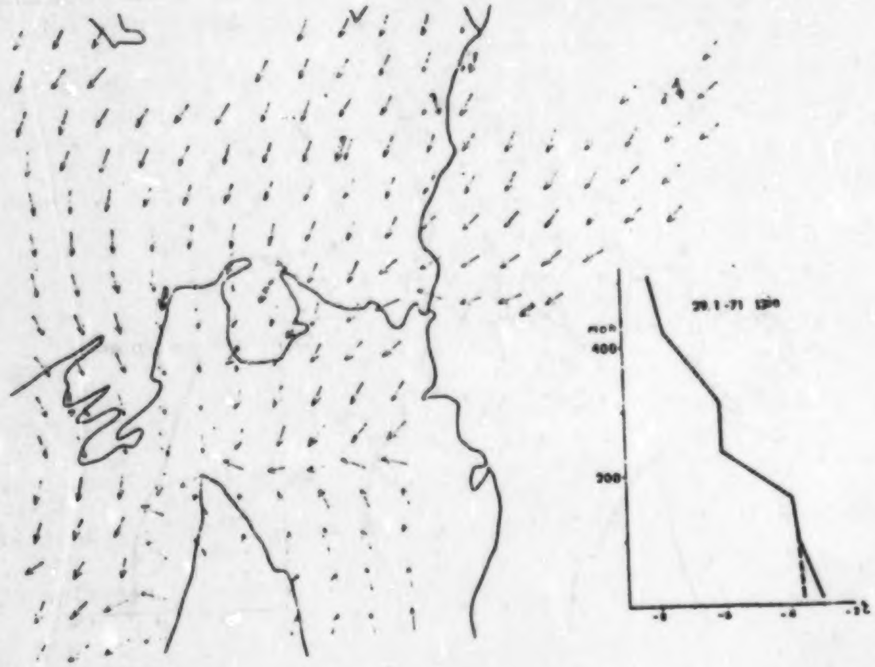

29.1 -71 1200
m
400
200
-8
-6
-4
-2

Fig. 10

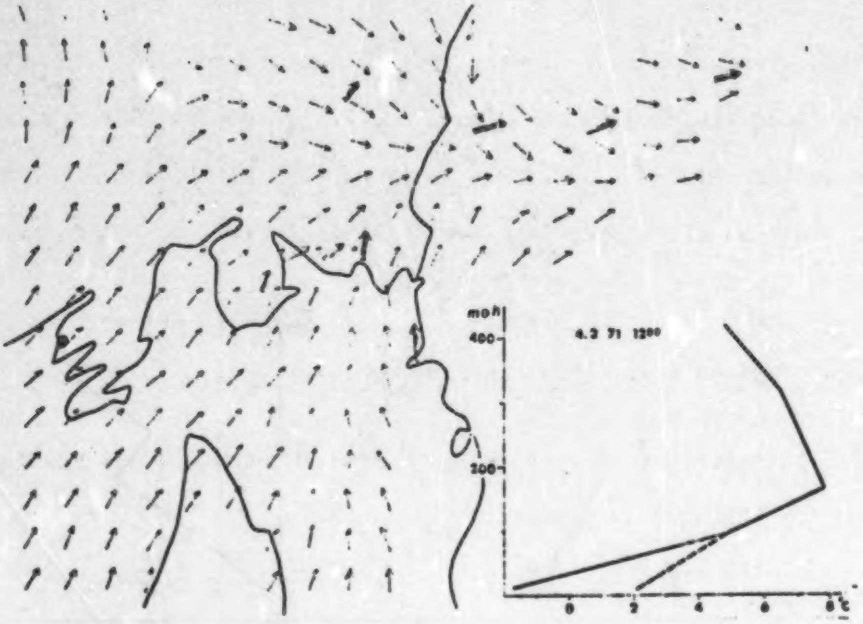

moh
400
200
4.3 71 12⁰⁰
0
2
4
6
8 °C

Fig. 11

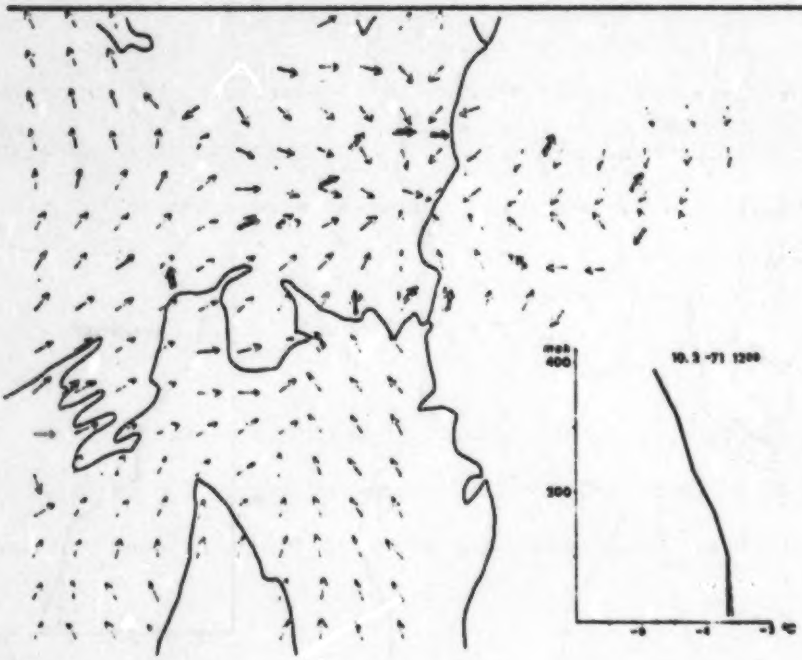

moh
400
200
10.3 -71 12⁰⁰
-8
-4
-3 °C

Fig. 12

Nydalen (V_3) (on which the computations are based) has been influenced by a local wind field which could have caused the discrepancies between observed and calculated winds. The observed wind at Blindern (V_3) indicates that an air stream from south is realistic in the northern part too.

Case Study 8: 12:00 a.m., 10th February 1971 (Fig. 12)

The vertical temperature structure is neutral. The main features in the observed wind field is matched in the calculation. In the western part, the observed wind directions are more perpendicular to the shoreline than calculated. Discrepancies like these are often observed and seem to be due to local effects in that part of Oslo.

Case Study 9: 12:00 a.m., 23rd February 1971 (Fig. 13)

The vertical temperature stratification is moderatley stable. The general air stream is from the south-west and the stagnation point is moved to the north-east relative to the maximum convergence zone. The calculated and observed wind directions match well.

Case Study 10: 2:00 p.m., 4th March 1971 (Fig. 14)

The vertical temperature stratification is moderately stable. The general wind field comes from north-east and no stagnation point is neither observed nor calculated. The observed and calculated wind directions match well.

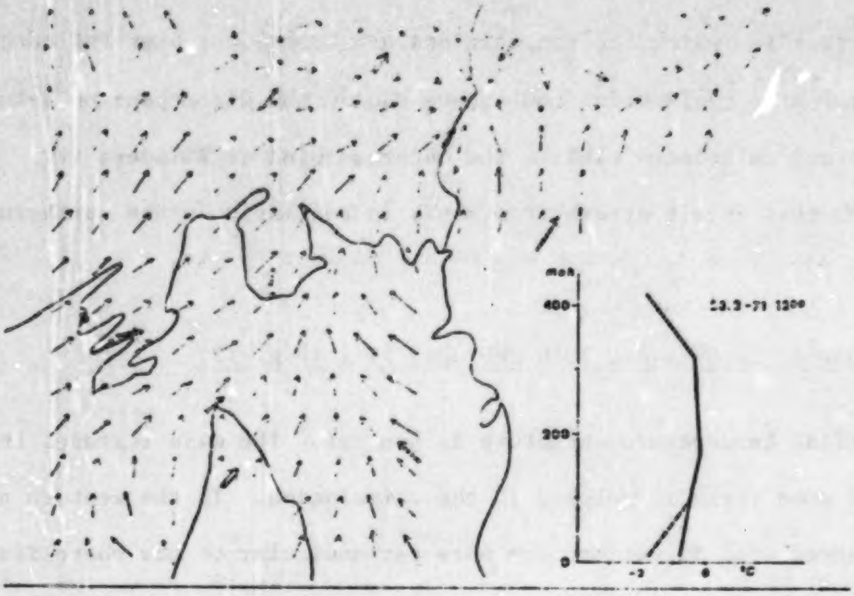

mb
400
200
0
-2
0
°C
23.3-71 1200

Fig. 13

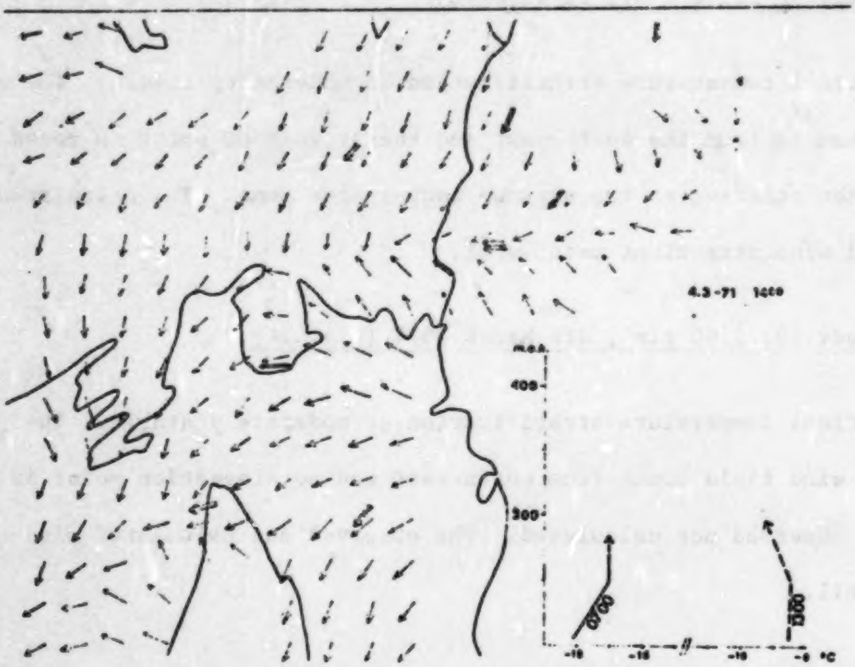

4.3-71 1400
m
400
200
0700
1300
°C

Fig. 14

Case Study 11: 1:00 p.m., 5th March 1971 (Fig. 15)

This is a typical wind field in air pollution situations in Oslo. The air flows down the valleys and out of the Oslo-fjord. The wind blows northward in the south-eastern part. The stagnation point is observed over the center of the city, close to the convergence zone. The calculated and observed winds match well.

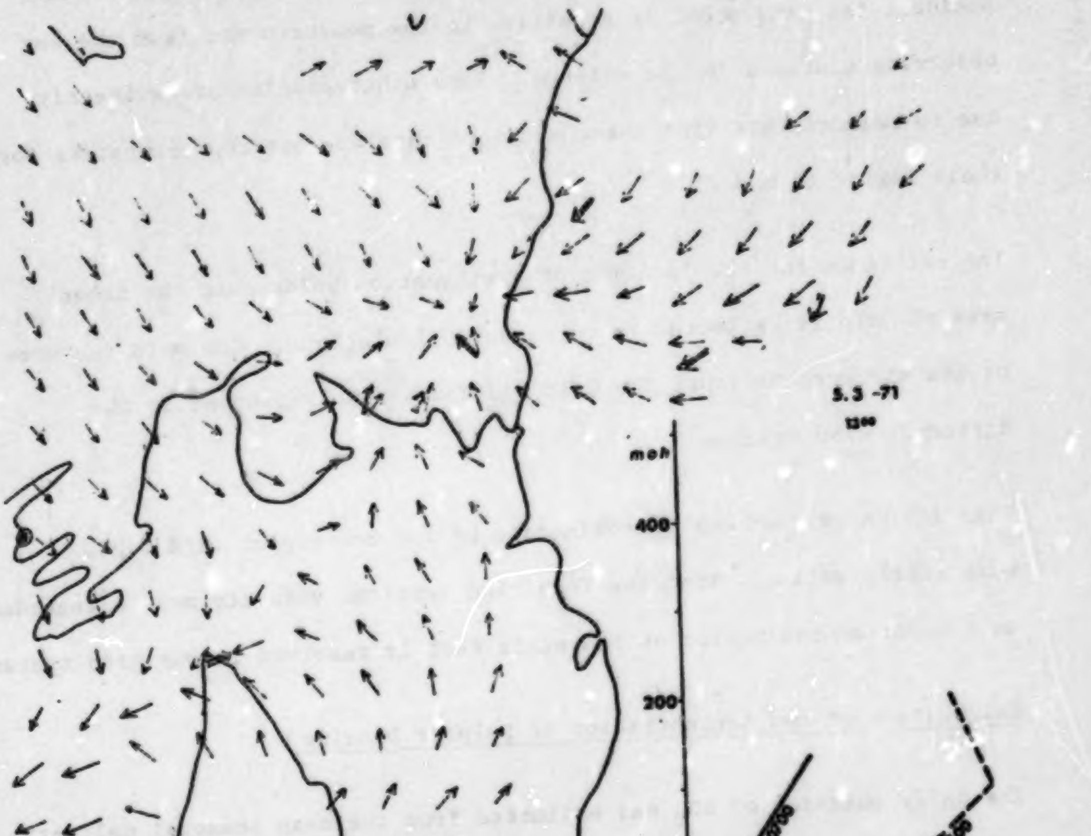

5.3 -71
1200
moh
400
200
0700
1300
-18
-17
-16
-6
-5
-4
-3
°C

Fig. 15

Summary of the Case Studies

In some case studies (1, 5, 6 and 7), the presented wind model does not work well in some regions in Oslo. This may be due to local canalization of the air flow which is not resolved in the model, or to wind fluctuations which the semi-stationary wind model does not take into account. Besides, the wind model is sensitive to the measurements from the key observing stations in the valleys. Some discrepancies are evidently due to measurements from these stations that are not representative for their region (4 and 7).

The existence and the location of a stagnation point over the urban area of Oslo is reflected in our model calculations. The main features of the air streams round the Oslo fjord are also reflected in the different case studies.

This indicates that our approximation of the convergent wind field work fairly well and that the resulting vertical velocity may be regarded as a first approximation on the scale that is resolved in our grid system.

Calculation of the Concentration of Sulphur Dioxide

The daily emission of SO_2 was estimated from the mean seasonal delivery of sulphur in oil by using the daily degree-day number and the seasonal sum of these numbers. The degree day-number denotes how many degrees centigrade the daily mean temperature is below 17°C. The hourly emission was estimated from the daily emission fluctuations proposed by Halpern, Simon and Randell in their study in New York (10).

The sinkterm of SO_2 (A) was assumed to be a function of the SO_2 concentration in the following way:

$$A = cq + dq^2$$

$c = 1.0 \cdot 10^{-6}\ s^{-1}$

$d = 0.25\ s^{-1}\ (g/m^3)^{-1}$

The functional form of A and the values c and d are estimated by J. Nordø in connection with modelling regional transport of air pollutants.

The wind model was used together with the presented estimates of the sources and sinks for SO_2 in the region, and the SO_2 concentration was calculated in all the grid points during the four days: 17th-18th December 1970, 3rd-4th January 1971, 4th-5th January 1971, and 5th-6th January 1971.

The timing of the daily measurements was the reason for chosing the calculation interval from 2:00 p.m. to 2:00 p.m. the next day. The initial value of SO_2 concentration was chosen to be zero. This approximation will influence the calculations during the first few hours. There was not found any reason to improve this approximation although it could easily be done, as for example, by using the steady state solution for the given wind field as an initial value.

The hourly mean SO_2 concentration measured at four stations was compared with the calculated values at the grid point within the same square kilometer.

Two of the stations, St Olavs-Plass and St Hanshaugen were in the center of the city (Fig. 1). The difference in height between these stations was about 70 m. It did not seem that this difference made any deviation in concentration. This supports our assumption of mixing in the lowest layer. The two other stations were placed south (Bygdöy) and north (Kjelsås) of the city center.

Figure 16 shows the calculated and observed values at the four stations from 3:00 p.m. the 17th December to 2:00 p.m. the 18th December. During the night, the windspeed slowed down from about five meters per second to an irregular wind of about 1 meter per second. This is the reason for the increase of the SO_2 concentration that is observed and calculated.

The calculated increase at St Olavs-Plass is too low compared to the observed values. It is possible that an investigation of such discrepancies might be used to improve the model, but no acceptable explanations have been found. An increase from about 100 µg SO_2/m^3 to about 300 µg SO_2/m^3 at St Hanshaugen and an increase from about 30 µg SO_2/m to 100 µg SO_2/m^3 at Bygdöy compared well. The calculations at Kjelsås do not show any large change, and the measurements do not show any fluctuation at all. The reason for this may be the limited sensitivity of the instrument used.

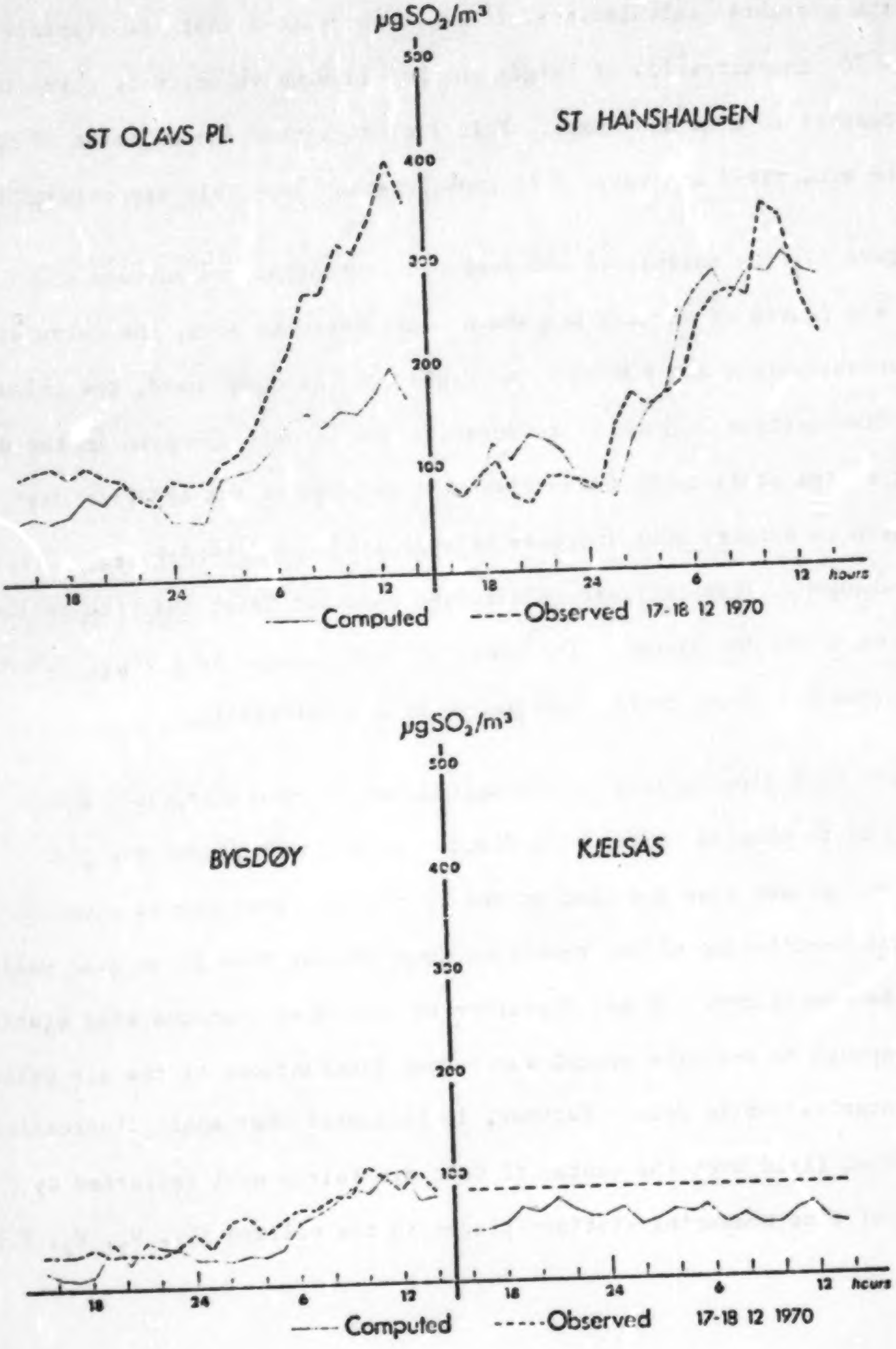

µgSO₂/m³
500
400
300
200
100
ST OLAVS PL.
ST HANSHAUGEN
18
24
6
12
18
24
6
12
hours
—— Computed
---- Observed
17-18 12 1970
µgSO₂/m³
500
400
300
200
100
BYGDØY
KJELSAS
18
24
6
12
18
24
6
12
hours
—— Computed
---- Observed
17-18 12 1970

Fig. 16

From the presented calculations, it may be concluded that the response of the SO_2 concentration of larger changes in wind velocity is correct with respect to time and space. This indicates that the emission of SO_2 and the wind field are taken into consideration as a fair approximation.

In Figure 17, the calculated and observed concentrations between the third and fourth of January are shown. All over the area, the calculated SO_2 concentrations are somewhat too high. On the other hand, the calculated fluctuations of some hours duration are largely observed in the same manner at the stations St Olavs-Plass, St Hanshaugen and Bygdöy. One exception is a three hour increase between 1:00 and 3:00 a.m. at St Hanshaugen. This increase is observed somewhat later and with smaller amplitude at St Hanshaugen. The reason for this might be a local increase of the emission which is not considered in the calculation.

The short term fluctuations in the calculated SO_2 concentrations are mainly due to changes in the wind field. These fluctuations are not easily recognized when the wind at one of the wind stations is studied. The total ventilating effect resulting from the air flow in several valleys has to be considered. It may therefore be concluded that one wind station is not enough to describe actual short term fluctuations of the air pollution concentration in Oslo. Further, it indicates that small fluctuations in the wind field over the center of Oslo are fairly well reflected by the net of wind measuring stations placed in the valleys (V_1, V_2, V_3, V_4).

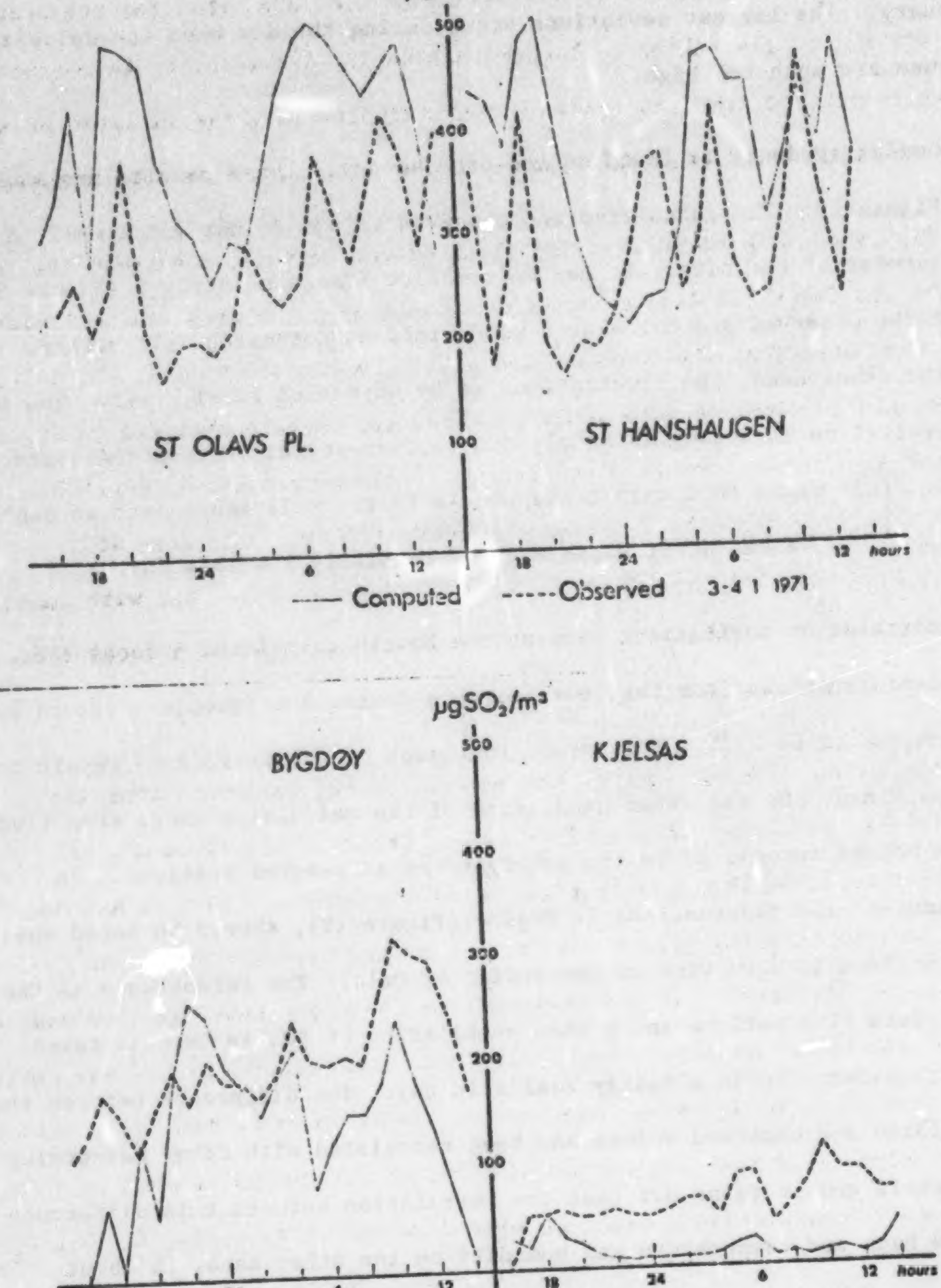

µgSO₂/m³
500
400
300
200
100
ST OLAVS PL.
ST HANSHAUGEN
18
24
6
12
18
24
6
12
hours
—— Computed
----- Observed
3-4 1 1971
µgSO₂/m³
500
400
300
200
100
BYGDØY
KJELSAS
18
24
6
12
18
24
6
12
hours
—— Computed
----- Observed
3-4 1 1971

Fig. 17

Figure 18 shows the measured and calculated values between the 4th and 5th January. The largest deviations occur during the day when the calculated values are much too high.

A similar tendency is found on the 6th January. These results are shown in Figure 19. The calculated and observed values do not match well in the center of the city. It may be recalled from case study 5 (Figure 9), that the observed and calculated wind field do not match well either. On the other hand, the fluctuations at Bygdöy match fairly well. The SO_2 concentration at Bygdöy is mainly due to transportation from the center of Oslo. This means that this transport is fairly well taken into account. The observed values at St Hanshaugen is specially low this day.

The correlation coefficient between the hourly calculated and observed SO_2 concentrations from the four stations during the four days turned out turned out to be 0.75. This means that much of the variations remain to be explained. On the other hand, many of the calculated short term fluctuations may be recognized in the observations at several stations. In particular, the fluctuations at Bygdöy (Figure 19), should be noted when this station is down wind of the center of Oslo. The resemblance in the short term fluctuations shows that ventilation of SO_2 in Oslo is taken into consideration in a fairly realistic way. The difference between the calculated and observed values has been correlated with other meteorological parameters and it turns out that the correlation between this difference on one hand and temperature and humidity on the other hand, is about

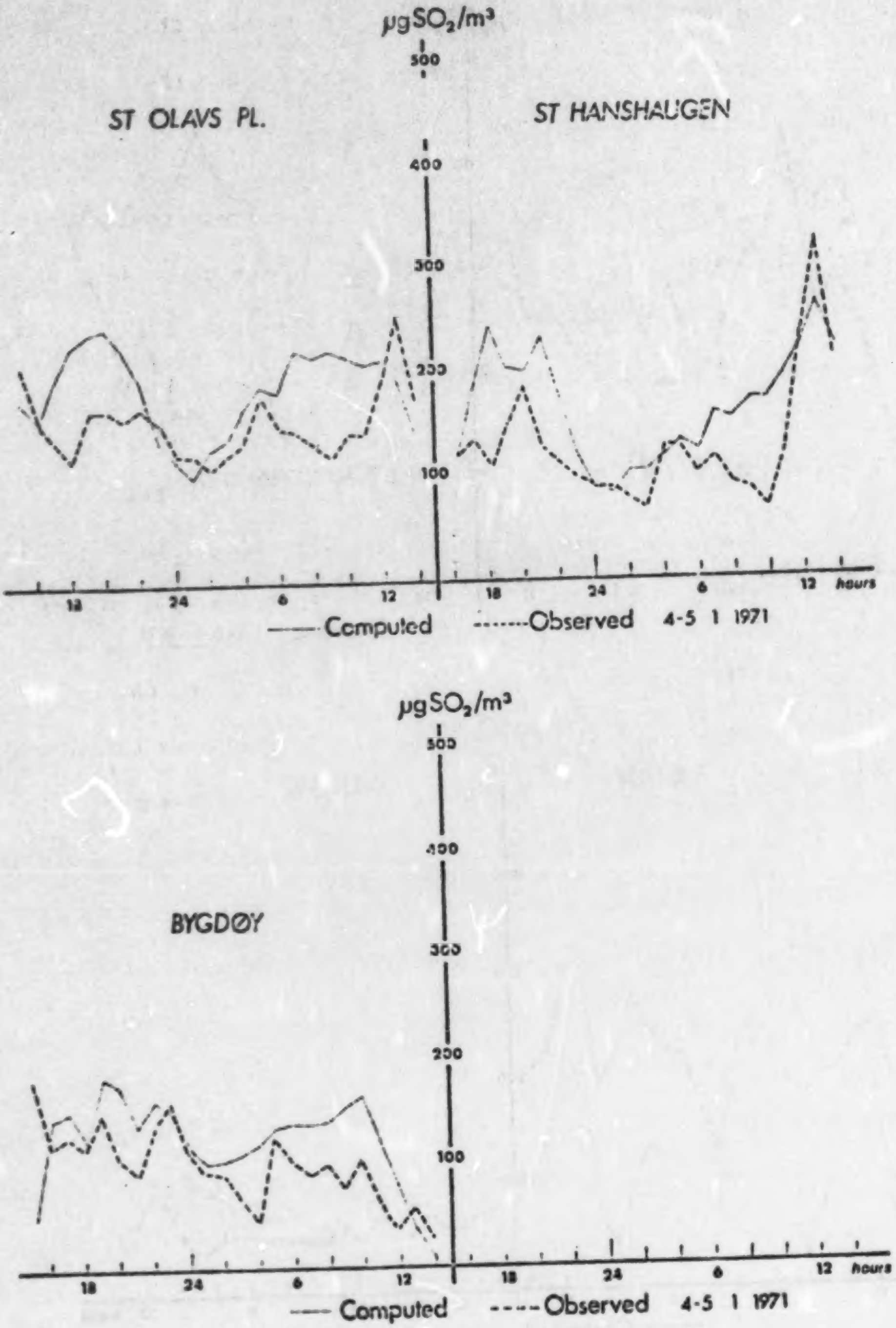

μg SO$_2$/m^3
500
400
300
200
100
ST OLAVS PL.
ST HANSHAUGEN
12
24
6
12
18
24
6
12
hours
Computed
Observed
4-5 1 1971
μg SO$_2$/m^3
500
400
300
200
100
BYGDØY
18
24
6
12
18
24
6
12
hours
Computed
Observed
4-5 1 1971

Fig. 18

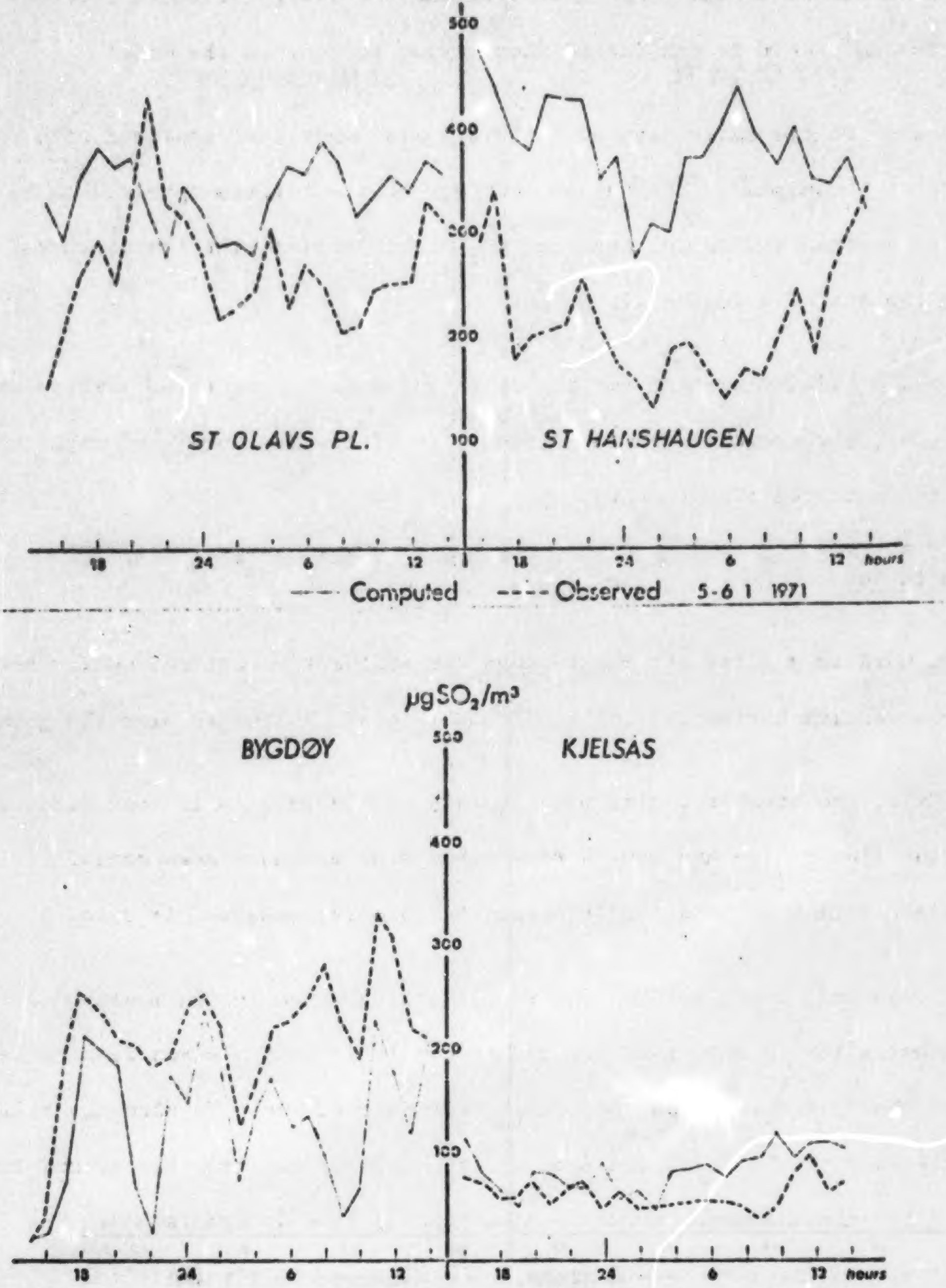

µgSO₂/m³
500
400
300
200
100
ST OLAVS PL.
ST HANSHAUGEN
18
24
6
12
18
24
6
12
hours
—— Computed
---- Observed
5-6 1 1971
µgSO₂/m³
BYGDØY
KJELSÅS
500
400
300
200
100
18
24
6
12
18
24
6
12
hours
—— Computed
----- Observed
5-6 1 1971

Fig. 19

0.80 on all stations. This indicates that more sophisticated chemical processes should be considered when trying to improve the model.

The dust on the daily exposed filters in Oslo has been analyzed with respect to sulphur. The sulphur content on the filters appeared to be closely connected to the measured SO_2 concentration, the temperature and the humidity in the air.

If the applied sink-term for SO_2 is regarded as a source for particulate sulphur, the computed concentrations were of the same order of magnitude as the referred measurements.

Conclusion

This work is a first attempt to consider systematic vertical motion and unhomogeneous horizontal motion in modeling air pollution near the ground.

In Oslo, the presented wind model worked fairly well in 11 case studies during winter time and gave a reasonable wind estimate even during periods with weak wind conditions that are often observed in Oslo.

Although only about half of the short term variance in the measured SO_2 concentration is explained, it may be concluded that the ventilation is taken into consideration in an approximatively correct way. To show the relative importance of the different removal processes of SO_2 from the ground level in Oslo, the different terms of equation (2) were integrated over the Oslo region, and the results are given in percent of the SO_2 emission:

- removal by vertical transport: 40 - 80%
- removal by horizontal transport: 0 - 50%
- removal by the applied sinkterm: 5 - 20%

Due to the organized vertical lifting of the air over Oslo, the SO_2 pollution within the city remains tolerable, despite the high frequency of stagnating periods during winter.

References

1. Lindberg, W., Den Alminnelige luftforurensning i Norge, Rökaderadet, Oslo 1968.

2. Wanta, R. C., Mathematical Models of Urban Air Pollution, Air Pollution Vol. 1, p. 215, edited by A. C. Stern, Academic Press, New York, London, 1968.

3. Neiburger, M., Diffusion Models of Urban Air Pollution, Technical Note No. 108, World Meteorological Organization, WMO, No. 254, TP 141, p. 248.

4. Peterson, J. T., The climate of cities, a survey of recent literature, U. S. Department of Health, Education and Welfare, October 1969.

5. Kohn, R. E., Abatement Strategy and Air Quality Standards, Development of Air Quality Standards, edited by Arthur A. Eriksen and Richard S. Gaines

6. Reiquam, H., Preliminary Trial of a Box Model in the Oslo Airshed, Proceedings of the Second International Clean Air Congress, Washington, D. C., December 1970.

7. Grønskei, K. E., A Time Dependent Numerical Dispersion Model for Air Pollution with Application to the City of Oslo, Norwegian Institute for Air Research, Kjeller 1971.

8. Skogvold, O. F., Luftforurensningen i Oslo, En statistic Bearbeidelse, Del 2, NILU Oppdragsrapport nr 15/70. Norwegian Institute of Air Research, Kjeller, 1970.

9. Nordø, J.,,Preliminary Notes on Large Scale Mass Transport, Lecture held at the von Karman Institute for Fluid Dynamics, March 22-26, 1971, Fluid Mechanical Aspects of Pollution.

10. Halpern, P.,C. Simon, and L. Randall, Source Emission and the Vertically Integrated Mass Flux of Sulphur Dioxide Across the New York City Area, J. of Applied Meteorology, Vol. 10, No. 4, 1971.

☆U.S. GOVERNMENT PRINTING OFFICE:1973 514-151/160 1-3